Report No. FHWA-RD-76-167

PREVENTION OF PREFERENTIAL BRIDGE ICING USING HEAT PIPES

September 1976
Final Report

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FOREWORD

This report describes the results of a study which investigated the use of heat pipes and renewable energy sources (specifically earth heat and solar energy) for preventing preferential icing of highway bridge decks, i.e., the bridge deck is icy but the adjacent roadway is not. The heat pipe system described is only suitable for new construction or major reconstruction.

Such bridge deck installations are estimated to cost between \$13 and \$18 per square foot of bridge deck with little or no maintenance required. The amortized costs over 30 years with 10 percent average interest are between \$1.08 and \$1.50 per square foot per year. Typical overall snow and ice removal costs are 1 cent to 2 cents per square foot per year. Clearly, heat pipe installations are too costly for widespread usage at the present time. They should be reserved for those ramps and bridge decks which are especially critical and require unusual efforts to remove snow or prevent preferential icing.

Earlier heat pipe research at Fairbank Highway Research Station provided design information for pavements. It led to a heat pipe installation on a ramp in West Virginia which has successfully melted snow and ice through one of the severest winters on record (1976-77).

The study was conducted for the Federal Highway Administration, Office of Research, Washington, D.C., under Contract DOT-FH-11-8545.

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D. Solomon

for Charles F. Scheffey
Director, Office of Research
Federal Highway Administration

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Federal Highway Administration Contract Manager: P. Brinkman, HRS-41
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16. Abstract

This report describes the results of a 27 month analytical and test program to investigate the use of heat pipes and renewable energy sources (specifically earth heat) to avoid the preferential freezing of highway bridge decks. Based on computer simulations of typical preferential icing events (days), a single system design is recommended for most U. S. locations. This design consists of nominal 0.5 inch heat pipes at the slab mid-plane, on 23 cm centers, connected to nominal 2 inch heat pipes in the ground via a pumped fluid loop, with 1 m of earth heat pipe provided for every 0.3 m^2 of bridge deck. The report also provides preliminary assessment of the design requirements and costs of an alternate, solar collector design; it concludes that the solar collector design may offer economic advantages over the earth heat pipe system, and thus should be investigated further.

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Section 1

INTRODUCTION

Although the preferential freezing (icing) of highway bridge decks is a relatively infrequent occurence, it is responsible for approximately 23,000 accidents annually, with an associated cost of 70 million dollars, Reference 1. Preferential icing is the freezing of a highway bridge, commonly called an overpass, with the adjacent roadway kept from freezing by contact with the warmer earth beneath it. Various methods of eliminating this condition have been tried, including the use of electrical resistance heaters and pumped fluid loops embedded in the deck. However, none has been found to be totally acceptable. Typically, state highway departments post signs to warn motorists that bridge decks freeze before the adjacent roadway. Since these signs are either activated by unreliable sensor systems, which may indicate icing under clear conditions, or are permanently visible throughout the winter, many motorists disregard them entirely.

In an earlier study, FHWA investigated the application of using heat pipes to prevent roadways from freezing using nuclear waste heat (Reference 2). However, this concept was judged impractical due to safety considerations, and the study subsequently considered the use of earth heat. Since it was shown that earth heat pipe systems would be expensive to install, it was decided to investigate the concept of earth heat and heat pipes to avoid limited, but particularly hazardous icing conditions.

The many problems imposed by preferential icing prompted the Federal Highway Administration to issue a contract to the Grumman Aerospace Corporation to investigate the use of heat pipes and earth heat to prevent the preferential icing of highway bridge decks. The contract initially covered a two-year analytical study to evaluate the technical and economic feasibility of this concept; however, since preliminary analytical results indicated the criticality of certain items of hardware, the scope was increased to 27 months to include component testing. This final report documents the total program results, including analytical and test phases, which began in July 1974 and was completed in September 1976.

Section 2

TECHNICAL DISCUSSION

2.1 SUMMARY

The first half of this study was devoted to preliminary thermal analyses to identify the key thermal parameters that influence the design of preferential de-icing systems for highway bridge decks. These analyses showed that the earth can provide a significant quantity of heat during cooler months, and recover over warmer periods; and that the rate of energy required to avoid preferential icing and the length and frequency of events are the parameters with greatest effect on the heat pipe spacing (in the deck) and the total number of earth heat pipes required. An additional result of these initial studies was a verification of the fact that limiting the energy withdrawn by the earth heat pipes through the use of valves would significantly decrease the number of earth heat pipes and land volume required. It was shown that one linear metre of a 2 inch, nominal, earth heat pipe coupled to 0.30 square metre of bridge deck surface would prevent preferential icing for a New York City site. It was also concluded that a relatively simple control system which senses both bridge deck and adjacent roadway surface temperatures could be used to control the earth heat pipe valves. A complete description of the effort performed during the first twelve months of this study is presented in Reference 3.

During the second part of the study, which is completely documented in this report, detailed transient analyses of system performance were performed for three sites: New York City, Oklahoma City, and Fresno, California. Based on a review of recorded weather data, specific days (events) during which preferential icing might have occurred were chosen. An analysis of a bridge deck and adjacent roadway surface was then made to verify that preferential icing did occur for the day (or days) chosen. Finally, an integrated computer model of the earth heat pipe/bridge deck slab was run to evaluate the ability of the design to avoid preferential icing. This analysis was performed for different bridge heat pipe spacings and control systems.

The same basic heat pipe system design was verified as being adequate for all three selected sites: 2 inch, nominal, earth heat pipes coupled to 0.5 inch, nominal, bridge heat pipe on 23 cm (9 inch) centers at the slab mid-plane, such that each linear metre of earth heat pipe is connected to 0.3 square metre of bridge deck (or, one linear foot of earth heat pipe is provided for each square foot of deck). However, the mass of earth required differs for each site, depending on the annual energy demand. Moreover, though a simple absolute and differential temperature algorithm would perform satisfactorily for New York City and Oklahoma City, inclusion of a dew point sensor would be desirable for climate locations typified by Fresno, California.

The analytic study pointed out certain hardware elements that would have a major impact on system design: specifically, the performance of valved heat pipes, the thermal resistance between the bridge heat pipes and the concrete slab, the resistance between joined heat pipes, and the ability of the earth to provide energy at the high rate required to avoid preferential icing. Hence, the scope of the effort was increased to include testing of these elements.

The major result of the test program was that heat pipe to heat pipe connections (joints) that would be suitable for field installation are inefficient, and long joint lengths must be used to limit the temperature drop from the earth to the bridge deck to acceptable levels. This inefficiency makes a total heat pipe system impractical; earth and bridge heat pipes would be more efficient if they were coupled with a pumped fluid system. Although such a system requires a pump which consumes some power, system performance is improved and the heat pipe control valves are eliminated.

Economic evaluations indicate that the earth heat pipe design recommended in this report will cost about $215/m^2 ($20/ft^2) of bridge deck, which is in the same price range as existing de-icing systems. Preliminary evaluations of a solar collector system, however, showed that this approach offers cost advantages over the earth heat pipe system, and warrents more detailed consideration.

2.2 EARTH HEAT PIPE SYSTEM DESCRIPTION

The greatest portion of this study to avoid preferential icing was devoted to consideration of a total heat pipe system connecting the earth source to the bridge deck. Due to the elevation of bridge decks, the use of integral pipes inserted into the ground and bent into the deck slab, as has been considered for highway de-icing applications, figure 1, is impractical. For highway bridges (overpasses), the heat pipes would have to be inserted into the ground, the pipes bent and brought-up the bridge pilings, and finally bent into the deck slab. Except for very small spans, this would require excessively long heat pipes (>60 metres) which would be difficult to transport to the site and handle, even if flexible sections were incorporated. Additionally, for every heat pipe required in the bridge slab, which would be on 15 to 23 cm (6 to 9 inch) centers, a pipe would have to be inserted into the ground and carried up a bridge piling. This approach, which would require the attachment of a large number of heat pipes to the bridge pilings, would be aesthetically unacceptable to the bridge designers and highway engineers.

The three-part heat pipe system design that thus was developed consists of earth, header, and bridge heat pipes, figure 2. Such a system simplifies installation, and should minimize jurisdictional disputes between construction trades. A drilling crew would insert the earth heat pipes into the soil; either the same or another crew could then attach a number of these earth heat pipes to header heat pipes, which would then be brought up the bridge piling and along the bridge deck. Flexible sections within the headers might be included, so that they could be bent during transportation to the site and thus simplify field bending problems. Finally, the soil-to-bridge deck

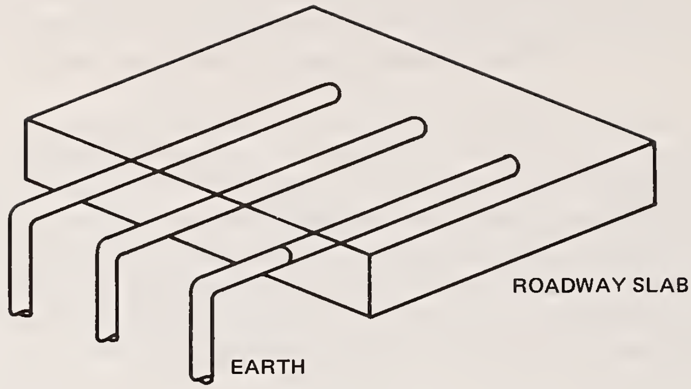


Figure 1 Typical heat pipe highway de-icing system

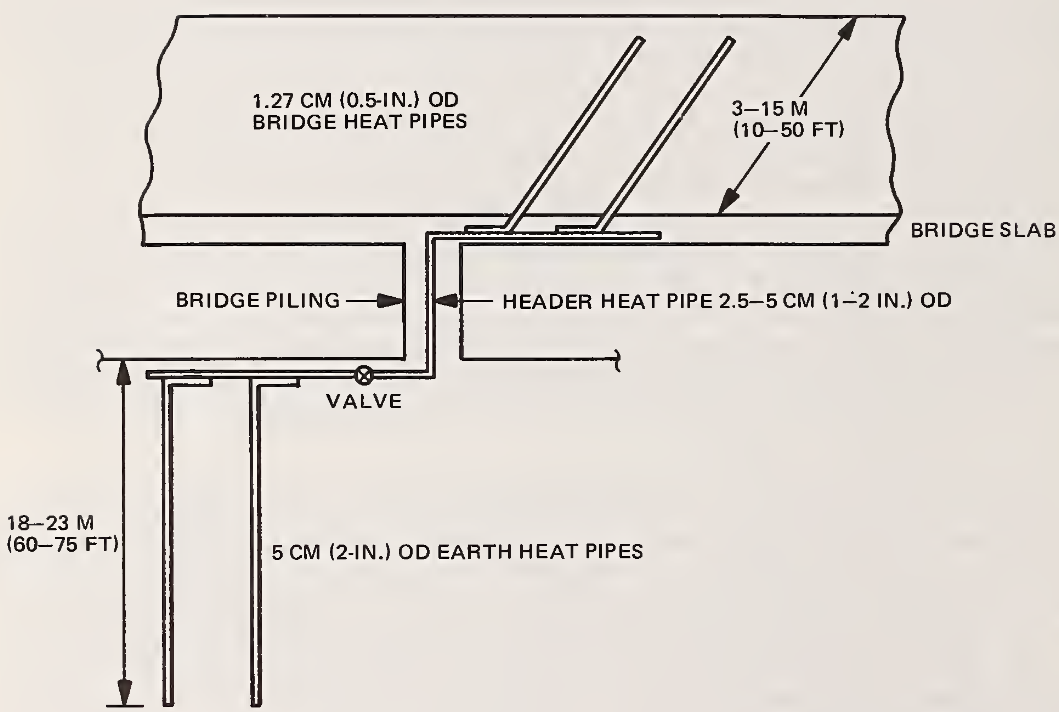


Figure 2 Cross section of typical heat pipe bridge de-icing system

circuit would be completed by joining the header pipes to the bridge heat pipes, which are laid in the deck prior to the concrete pouring. The earth heat pipes would be joined to the headers below ground level and the headers insulated to minimize heat leaks to the environment.

With the heat pipe circuit described, heat would be extracted from the earth whenever the temperature of the air was lower than that of the soil. Since this would require a very large earth mass to prevent sub-cooling, a valve is included in each header heat pipe. These valves are controlled by sensors contained within the bridge deck and adjacent roadway surfaces; a control logic activates the valves whenever the sensors indicate the onset of preferential icing conditions. Initially, ice sensors were considered for this purpose. However, since literature searches and manufacturer contacts were unsuccessful in discovering any reliable ice detectors, the use of that type of sensor was eliminated and temperature and/or moisture sensors were substituted as baseline devices to activate the earth heat pipe systems.

Although a system with combined moisture and temperature sensors would consume the least energy of the systems considered, this is not the most reliable design. For example, if the design includes a moisture sensor which will detect liquid water, the system may not activate properly for a preferential icing condition caused by condensation. Though the primary cause of preferential icing in the northeastern United States is frozen precipitation, preferential icing also can occur due to other weather conditions. Thus, although a moisture/temperature sensor system might avoid the majority of preferential icing events, it would not totally eliminate the problem. Consequently, the most reliable design would be based on the use of simple absolute/differential temperature sensors. In order to function satisfactorily, a control system logic (algorithm) would have to be used to activate the earth heat pipes whenever the deck slab temperature was within a certain temperature band, and below that of the adjacent roadway. Although such a system would be active during dry periods in which preferential icing could not occur, less land is required than for a completely passive system, and reliability is greater than for a temperature/moisture and/or ice detector system.

2.3 STUDY PHILOSOPHY

The overall objective of this program was the development of earth heat pipe systems for avoidance of preferential icing on highway bridge decks. Separate systems were to be developed for a limited number of common-climate zones so that highway engineers could select an appropriate design for their location.

Initial plans were to subdivide the United States into three or four climate zones and to develop systems for at least four "standard" bridge types. One of these climate zones was to be a relatively severe location, such as Duluth, Minnesota or Casper, Wyoming; but, as available

literature was reviewed it became clear that icing or snow accumulation was more of a problem for these colder climates than preferential icing. Throughout a major part of the winter season, roadway surfaces will be exposed to below freezing temperatures and precipitation will be heavy. Under these conditions, it is likely that highway as well as bridge surfaces will freeze (or be covered with snow) and that preferential icing will not occur. Moreover, as icing is more common for these sites than many other locations, local motorists will be more alert to the possibility of hazardous driving conditions and be more familiar with safe driving procedures. In addition, due to the severity of these climates, it was felt that earth heat pipe systems would be expensive and not economically acceptable; a greater number of heat pipes and more land volume would be required than in milder climates. Hence, it was decided to consider three sites which would be more representative of locations where preferential icing posed an especially significant problem and could economically be avoided. In addition, since bridge design was considered to be a second-order effect, which would not significantly alter analytical results, a single basic bridge design was used to evaluate system performance and to develop design requirements.

As described in Reference 3, a review of climatic conditions recorded by the U. S. Weather Bureau was made to select sites for analysis. Based on discussions with FHWA, three sites were selected: New York City, Oklahoma City, and Fresno, California. In both New York and Oklahoma Cities, preferential icing is expected to occur primarily as a result of frozen precipitation. In Fresno, icing is more likely to be due to a drop in the deck surface temperature below both the freezing and dew point levels, causing direct formation of frost; e.g., on a cool, clear night, radiation to the atmosphere can result in a deck temperature which is lower than that of the adjacent roadway, freezing, and dew point temperature levels. As United States climate conditions are suitably represented by these three cities, system performance in other locations can be readily projected.

Our overall analytical approach was to build complete thermal models containing representations (nodes) of the earth, bridge deck, and adjacent roadway surfaces with and without the inclusion of an earth heat pipe system. The natural (or no-heat-pipe) model would enable the verification of preferential icing for specific weather conditions, and the integrated heat pipe model would enable verification of the ability of the heat pipe system to avoid preferential icing. (A description of the computer models is presented in Appendix B.) Rather than arbitrarily selecting climatic conditions for analyses, a number of years of weather data was reviewed to select typical events (days) during which preferential icing was likely. The natural model would then be run to verify the occurrence and the heat pipe model subsequently run to verify system performance.

2.4 SYSTEM VALIDATION

2.4.1 Preliminary System Analysis (New York City)

Initially, the integrated network was set up to represent 5 cm (2 inch) outer diameter (OD), 9 m (30 ft) deep earth heat pipes coupled to 3.7 m^2 (40 ft^2) of bridge surface via 1.27 cm (0.5 inch) OD bridge heat pipes on 15.25 cm (6 inch) centers at the slab mid-plane. A series of computer analyses were performed using this network to evaluate the influence of several significant parameters. Although the model was subsequently revised to reflect the final design configuration of one meter of 5 cm (2 inch) OD earth heat pipe per 0.3 m^2 (1 ft^2) of deck, coupled to 1.27 cm (0.5 inch) OD bridge heat pipes on 23 cm (9 inch) centers, several significant results were obtained from this initial model. The following paragraphs briefly review these evaluations, which are summarized in table 1.

Following our overall analysis plan, a review of weather conditions was performed to select days during which preferential icing was likely and system performance could be evaluated. Based on a review of 10 years of weather data recorded for New York City, two days were chosen for analysis: January 20 and March 14, 1975. January 20 was selected as being typical of a winter day when the air temperature quickly drops below freezing while precipitation is falling. The March 14 date was chosen as being representative of spring or fall conditions, when the air temperature remains near freezing for a long period while rain falls. In addition, in order to evaluate the energy drain for days when preferential icing is unlikely, the analysis considered the days following each of these events: January 21 and March 14, respectively. Since no precipitation occurred on each of these latter days, the energy demanded by the system for "dry" conditions could be evaluated. Tables 2 and 3 summarize the pertinent weather conditions recorded during each of these days.

Early in the study, a transient analysis was performed to evaluate the average monthly response of the earth as a function of depth from the surface. These system evaluations were initiated with the earth temperature profile, shown in figure 3, corresponding to our predictions for January.

In order to establish that preferential icing would occur on the days chosen, an analysis was performed without the heat pipe system. As shown in figures 4 and 5 (Case 1 and 2, table 1), this analysis indicated preferential icing periods of about 0.4 hour (24 minutes) and 4 hours for January 20 and March 14, respectively. Note that although January 20 is a colder day and has a wider temperature variation, the preferential icing period is longer on March 14 because the air temperature remains near the freezing point for a longer time. When the air temperature is near freezing, the roadway resists the tendency to cool below freezing longer than the bridge, since it is conductively coupled to the earth mass. On the other hand, if the air temperature were to drop rapidly below freezing, both surfaces would freeze nearly coincidently, and preferential icing would not occur. Thus, preferential icing is most likely when the air temperature is close to freezing for a long time.

Table 1 Preliminary Analytic Results – New York City

Case	Date, 1975	Initial Avg Earth Temp		Final Avg Earth Temp		Mean Earth ΔT		Earth Heat Provided to Bridge		Time System Active, hr	Avg Rate of Energy to Bridge		Comments
		°C	°F	°C	°F	°C	°F	kwh	Btu		watt/m²	Btu/hr-ft²	
1	1/20	10.7	51.3	10.41	50.74	0.32	0.58	–	–	–	–	–	Bridge Pipe Off
2	3/14	10.7	51.4	10.57	51.02	0.22	0.40	–	–	–	–	–	Bridge Pipe Off
3	1/20	10.7	51.3	10.24	50.44	0.49	0.88	0.85	2905	2.45	187	59.3	Bridge Pipe On
4	3/14	10.7	51.4	10.19	50.34	0.6	1.08	2.03	6924	6.34	172	54.6	Bridge Pipe On
5	1/21	10.2	50.4	4.97	49.95	0.33	0.49	0.40	1363	0.87	247	78.3	Bridge Pipe On
6	3/15	10.2	50.3	10.16	50.28	0.03	0.06	0.48	1650	1.34	194	61.6	Bridge Pipe On
7	1/20	8.0	46.4	7.63	45.73	0.38	0.69	0.68	2331	2.79	132	41.8	Initial Earth Cooling 2.8°C (5°F)
8	1/21	7.63	45.7	7.42	45.36	0.21	0.37	0.34	1185	1.02	183	58.1	Initial Earth Cooling 2.8°C (5°F)
9	3/14	8.11	46.5	7.62	45.71	0.45	0.81	1.6	5438	7.46	114	36.4	Initial Earth Cooling 2.8°C (5°F)
10	3/15	7.61	45.7	7.04	45.76	-0.03	-0.05	0.43	1495	1.70	138	44.0	Initial Earth Cooling 2.8°C (5°F)
11	3/14	10.8	51.4	10.23	50.41	0.56	1.01	1.7	5951	7.72	121	38.5	Joint Resistance, 105 W-°C
12	3/14	0.07	46.5	7.63	45.74	0.43	0.77	1.44	4983	9.47	83	26.3	Joint Resistance + Earth Cooling
13	1/20	10.6	51.2	10.00	50.00	0.64	1.16	0.78	2693	2.36	179	57.1	Uniform Initial Temperature
14	1/21	10.0	50.0	9.73	49.51	0.28	0.51	0.38	1340	0.95	248	78.8	Uniform Initial Temperature
15	3/14	10.8	51.4	10.61	51.09	0.19	0.34	–	–	–	–	–	Valve at Surface
16	3/14	10.8	51.4	10.61	51.09	0.19	0.35	–	–	–	–	–	Valve 5 Cm (2 in.) Below Surface
17	3/14	10.8	51.4	10.61	51.10	0.19	0.34	–	–	–	–	–	Valve 10 Cm (4 in.) Below Surface

Table 2 New York City Weather Data — Summary

Date	Temperature						Rainfall			Average Wind Speed	
	Max		Min		Avg						
	°C	°F	°C	°F	°C	°F	hr	cm	in.	m/sec	mph
January 20, 1975	3.9	39	−7.2	19	−1.7	29	12	0.38	0.15	7.6	17.1
January 21, 1975	1.1	34	−8.3	17	−3.3	26	0	0	0	4.7	10.5
March 14, 1975	3.3	38	−0.6	31	1.7	35	18	1.3	0.51	8.0	18.0
March 15, 1975	7.2	45	−1.7	29	2.8	37	0	0	0	7.9	17.8

Table 3 New York City Weather Data — Solar Load (1975)

Time, hr	Solar Load, Langley/cm^2 (Btu/hr-ft^2)					
	1/19	1/20	1/21	3/13	3/14	3/15
12	0	0	0	0	0	0
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	0	0	0	0	0	0.7 (2.6)
8	0.3 (1.1)	0	0	2.5 (9.2)	0	10.6 (38.9)
9	5.8 (21.3)	0.6 (2.2)	0	12.8 (47.1)	1.8 (6.6)	28.4 (104.4)
10	19.1 (70.2)	5.9 (21.7)	2.0 (7.4)	10.9 (40.1)	3.7 (13.6)	39.1 (143.7)
11	25.9 (95.2)	9.3 (34.2)	6.1 (22.4)	6.9 (25.4)	3.9 (14.3)	54.6 (200.7)
12 Noon	34.0 (124.9)	10.8 (39.7)	7.9 (29.0)	38.0 (139.7)	1.4 (5.1)	54.3 (199.6)
1	34.7 (127.5)	4.2 (15.4)	26.6 (97.8)	18.0 (66.2)	0.8 (2.9)	64.9 (238.5)
2	29.3 (107.7)	3.4 (12.5)	9.7 (35.7)	33.2 (122.0)	0.9 (3.3)	61.4 (255.7)
3	11.3 (41.5)	0.8 (2.9)	7.1 (26.1)	36.8 (135.3)	0.9 (3.3)	50.6 (186.0)
4	3.2 (11.7)	0.4 (1.5)	2.2 (8.1)	29.4 (108.1)	0.3 (1.1)	36.5 (134.2)
5	0	0	0.8 (2.9)	13.9 (51.1)	0.2 (0.73)	19.4 (71.3)
6	0	0	0	1.6 (5.88)	0	3.7 (13.6)
7	0	0	0	0	0	0
8	0	0	0	0	0	0
9	0	0	0	0	0	0
10	0	0	0	0	0	0
11	0	0	0	0	0	0
12	0	0	0	0	0	0

METRES	FEET	°C	°F
0.61	2	3.4	38.2
1.21	4	4.8	40.6
1.82	6	5.5	41.9
2.44	8	7.7	45.8
3.66	12	8.9	41.8
4.876	16	11.6	52.9
6.1	20	12.4	54.4
7.6	25	14.1	57.4
9.1	30	14.8	58.8
12.2	40	15.2	59.4
18.2	60	15.2	59.4
24.4	80	15.2	59.4

Figure 3 Predicted earth temperature profile

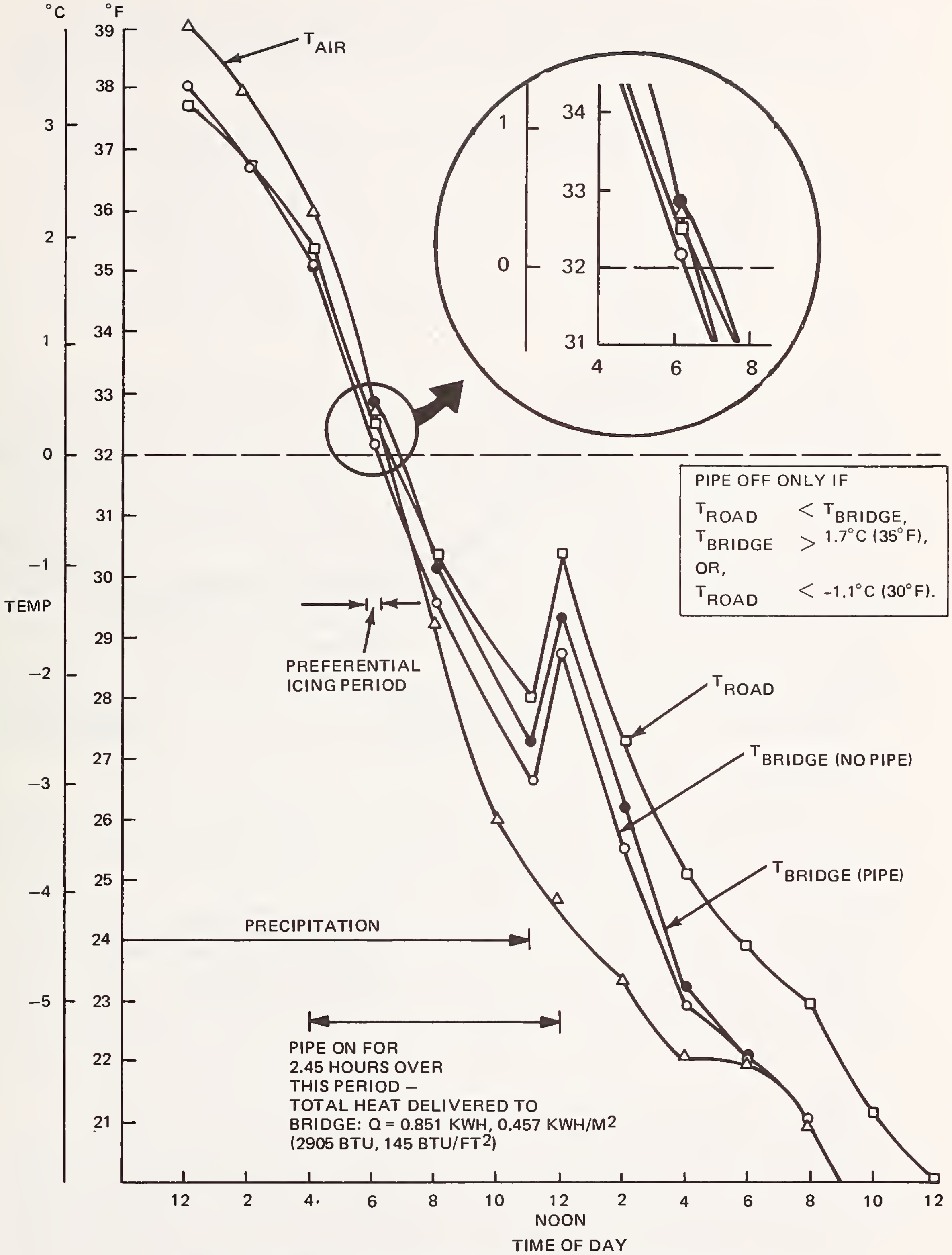


Figure 4 Ability of earth heat pipe system to avoid preferential icing for New York City bridge — January 20, 1975

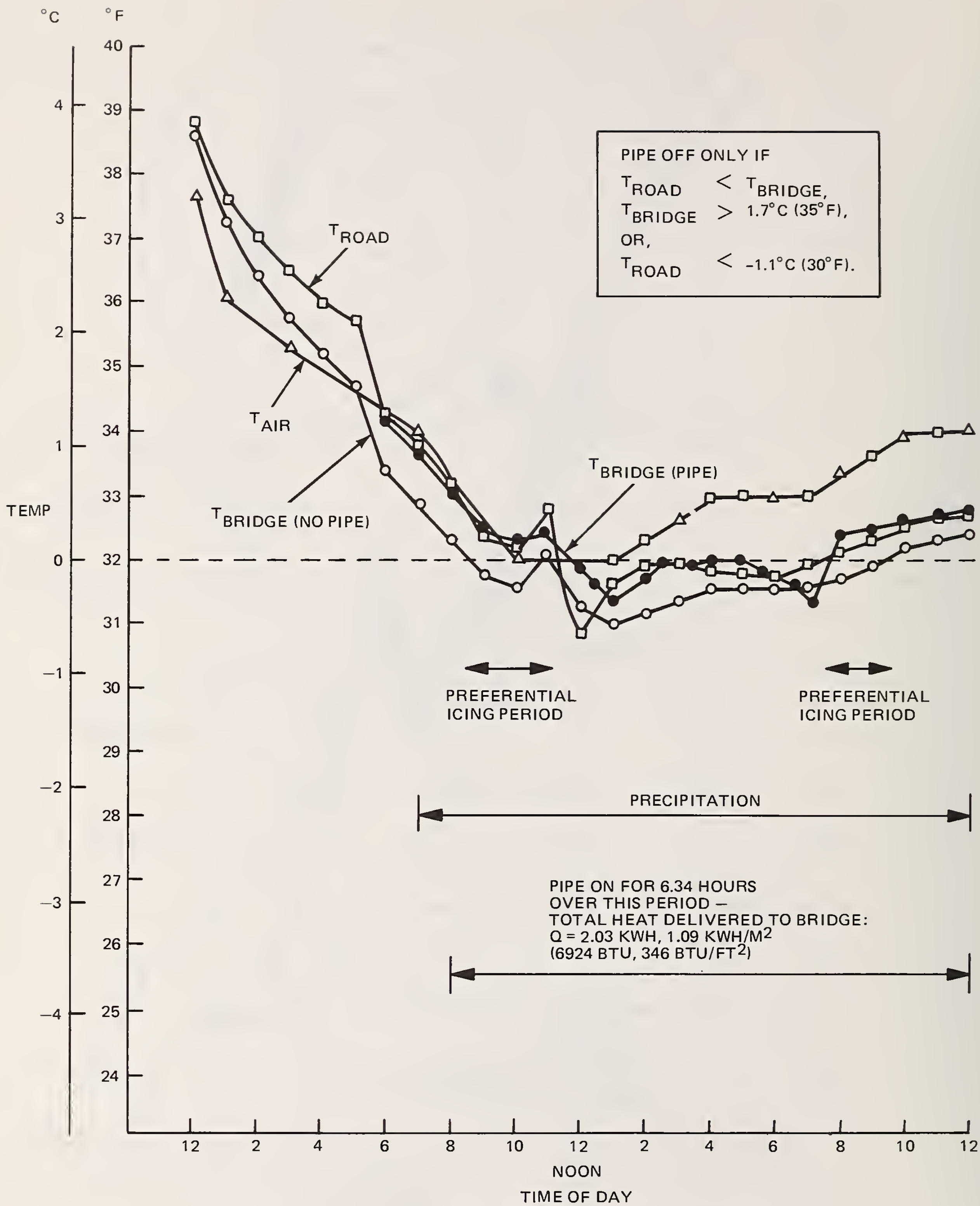


Figure 5 Ability of earth heat pipe system to avoid preferential icing for New York City bridge – March 14, 1975

In order to verify that the heat pipe system would prevent preferential icing, the analysis was repeated with the inclusion of earth and bridge heat pipes, with the earth heat pipe valves controlled by the following temperature algorithm:

Pipe off only if at least one of the following conditions exists:

$$T_{road} < T_{bridge},$$

$$T_{bridge} > 1.7°C\ (35°F),$$

$$\text{or, } T_{road} < -1.1°C\ (30°F).$$

These limits were chosen so that the earth heat pipe system would be active prior to potential icing events for both cool-down and warm-up situations. Figures 4 and 5 (Cases 3 and 4) verify the ability of the design to avoid preferential icing on both of the dates. As shown, preferential icing no longer occurs, since the bridge is warmed by the earth heat pipe whenever preferential icing is likely. The total energy removed from the earth for each of the analyzed days (Cases) is presented in table 1. As shown, 0.85 and 2.03 kwh (2905 and 6924 Btu) are removed on January 20 and March 14, respectively. With this type of valve control, a period of mild wet weather with temperatures near freezing requires more energy than does significantly colder days. This is verified by the results for January 21 and March 15, "dry" days following each of the preferential icing days. In both cases, the variation in air temperature is wide and the earth heat losses are small: 0.4 kwh (1363 Btu) and 0.48 kwh (1650 Btu) for January 21 and March 15 (Cases 5 and 6), respectively.

As shown in figure 3, the analysis predicted that the earth temperature would stabilize at about 15.6°C (60°F) for New York City. Actually, this temperature should approach the average annual air temperature, 12.8°C (55°F), for this site. The warmer analytical predictions are due to the neglect of energy terms to evaporate rain water, melt snow, etc, from the earth surface. In order to examine the effect of the actual, more severe earth temperature profile, the analysis was repeated with each nodal temperature decreased by 2.7°C (5°F), dropping the earth temperature to ~ 12.8°C (55°F) beyond ~ 9 m (30 ft). As expected, for all analyzed days the total heat removed from the earth decreased and the length of time the pipe was active increased (Cases 7 through 10, table 1). However, preferential icing was still prevented on both January 20 and March 14.

In order to evaluate the effect of heat pipe joints, the March 14 data were run for two more cases (11 and 12). For these evaluations, a joint resistance of 105 w/°C (200 Btu/hr-°F) was included in the model between the earth and bridge heat pipes. In the first case, the original earth temperature profile was used; although the system was still able to avoid preferential icing, there was a reduction in the heat provided to the bridge: about 464 w-hr/m^2 (149 Btu/ft^2) compared to about 545 w-hr/m^2 (173 Btu/ft^2) in the

jointless case, and an increase in active period from 6.34 to 7.72 hours. In the second case, the joint resistance and effect of a 2.7°C (5°F) cooler earth mass were combined. This resulted in a sizable reduction in the energy provided to the bridge: from about 545 w-hr/m^2 (173 Btu/ft^2) to about 493 w-hr/m^2 (125 Btu/ft^2), and an increase in the active period to 9.47 hours. In this case, the system failed to prevent preferential icing for brief periods. This analysis indicated that in order for the heat pipe system being analyzed to be completely functional for the entire winter season, steps must be taken to prevent excessive earth cooldown and to maximize joint conductance.

Reference 3 pointed out that local sub-cooling of the earth around the earth heat pipe could prevent de-icing. Although the system was intermittently active over a number of hours for each of the described cases, the integrated analysis showed that local sub-cooling of the earth was not a problem. This is because a relatively low energy rate was required for the analyzed events, 238 w/m (40Btu/hr-ft) of earth heat pipe, and the earth was capable of providing this energy. In order to verify the integrated model results, the radial earth model shown in figure 6 was set up. This network represents a 30.48 m (1 ft) thick cylindrical slice through the earth cylinder at some depth, say 7.62 m (25 ft) from the surface. Corresponding to the March 14 data, an analysis was performed assuming an energy drain of 39.4 w/m (41 Btu/hr-ft) of pipe for 6 hours. Initial nodal temperatures were input based on the conditions predicted by the integrated model at the onset of system activation for this typical event.

As shown in figure 7, the one dimensional model verified that local subcooling of the earth would not be a problem for this energy rate. The earth temperature in the immediate vicinity of the heat pipe dropped steadily in temperature from about 9.4 to 5.5°C (49 to 42°F) over the 6 hour period, and nearly recovered to its initial temperature in about 1 hour. The earth temperature profile was essentially restabilized six hours after the event, although at a slightly lower temperature level reflecting the energy removal. The analysis therefore verified that the system can provide a low energy drain for a significant time period and will recover rapidly following an energy demand period.

Since the earth heat pipes isothermalize the ground temperature vertically in the winter months, an analysis was run for the January dates with an initial isothermal earth temperature set at the average of the nodal temperatures previously used (Cases 13 and 14). As the results for this analysis were not significantly different than for the original runs made with a variation of earth temperature with depth, vertical temperature gradients were concluded to have no significant effect on system performance.

Even if the earth heat pipe is inactive (valve shut), the heat pipe brings heat from lower earth depths to the vicinity of the surface, thus increasing surface heat losses. Installing the valve at some depth below the surface naturally attenuates this added loss. Computer analyses that were performed to simulate the earth response with the valve at various depths below

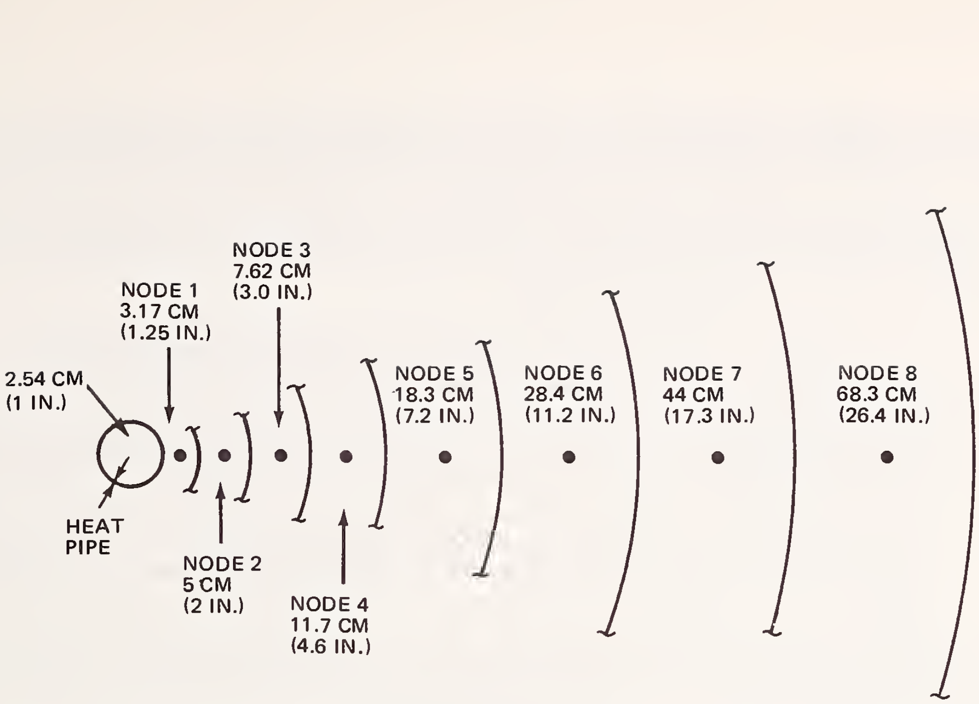


Figure 6 Radial earth model

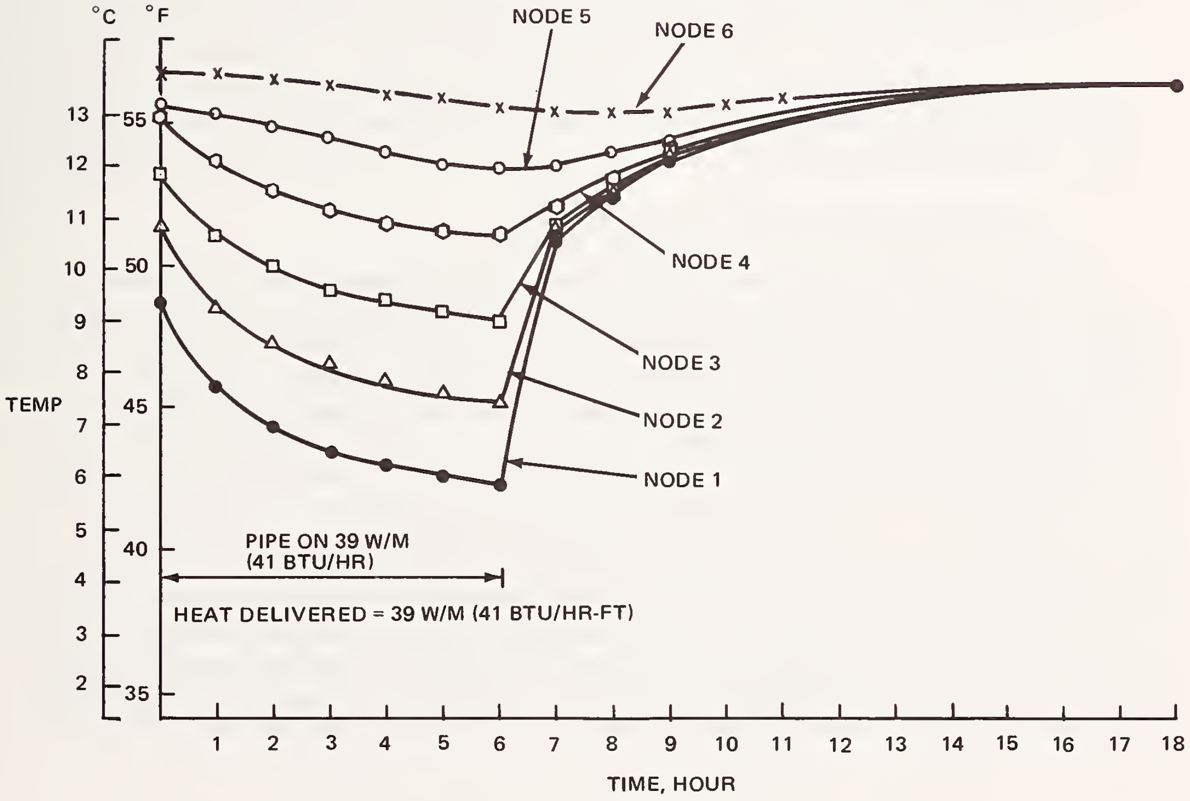


Figure 7 Earth cooldown and recovery from established radial temperature profile

the surface showed that locating the valve at a depth of 0.91 to 1.2 m (3 to 4 ft) would be sufficient to limit the energy drain from the earth (Cases 15 through 17).

The following conclusions were reached, therefore, based on the preliminary evaluations with our integrated model:

- A reasonable earth volume can provide sufficient energy to avoid preferential icing for winter events
- Preferential icing can be more severe in late winter/early spring than in mid-winter
- Extended periods of near-freezing temperatures will result in longer preferential icing periods than will sudden drops below the freezing point
- The resistance across heat pipe joints significantly affects system performance
- System performance with bridge heat pipes located at the slab mid-plane is satisfactory
- Although earth heat pipes reduce the natural temperature gradient in the earth, system performance is not significantly affected by this action
- Burying the valve 0.9 to 1.2 m (3 to 4 ft) below the surface is sufficient to minimize the influence of the earth heat pipe on the natural heat loss from the surface.

2.4.2 Final System Performance Verification

The described preliminary integrated model analyses led to the conclusion that, unlike general icing or snow accumulation problems, preferential icing occurs only when the air temperature is near freezing and is only slightly affected by the rate of precipitation. Therefore, the energy rate required to avoid preferential icing is nearly the same regardless of location, but the total energy required depends on the weather situation (temperature and precipitation time-histories). A single heat pipe spacing and location, in the bridge slab thus can be used since the source temperature (earth) does not vary greatly for much of the United States (we had previously concluded that earth heat is not economically feasible for very cold locations). Obviously, however, the land mass required varies with location in order to provide the total yearly energy required. In order to verify these initial conclusions, we decided to perform an integrated math model analysis of the de-icing system for New York City, Oklahoma City, and Fresno, California, using the same heat pipe design requirements for each site.

As in our preliminary studies, a review of weather conditions was made to select events (days) during which preferential icing appeared likely. A passive analysis was first made to verify that icing would have occurred; the model was then re-run with the earth heat pipe system included to demonstrate system performance.

2.4.2.1 New York City

A review of weather conditions over a 10 year period indicated that March 14, 1975 was a particularly severe event, with the most energy required to avoid preferential icing. Therefore, a number of computer runs were performed for this date to evaluate both the spacing of the heat pipes in the bridge deck and the earth pipe depth. Table 4 summarizes the energy required to avoid preferential icing in each of these cases.

The system that initially was evaluated had bridge heat pipes on 15.24 cm (6 inch) centers and 9.1 m (30 ft) deep earth heat pipes coupled to 1.86 m^2 (20 ft^2) of bridge surface area: an earth heat pipe length to bridge surface area ratio of 2 to 3. As shown in figure 8, in order to avoid preferential icing for March 14 with the temperature control system used, the heat pipe system is active for slightly more than six hours, and provides ~2 kwh (6840 Btu) to the deck (Case 1, table 4). Since the model assumes that the falling rain is frozen, it extracts latent energy (to melt the frozen rain) from the road and bridge surfaces whenever they are above freezing. Since the exact freezing point of rain water can vary slightly about 0°C (32°F), the model was built to extract energy from the bridge and roadway to melt the frozen rain whenever the surface temperature was above -0.4°C (31.3°F). When the surface temperature drops below this value, the latent load is neglected. This treatment is responsible for the sharp rise in the roadway surface temperature shown at 9 A.M., figure 8.

In order to examine the influence of bridge heat pipe spacing on system performance, Cases 2 through 4 of table 4 were run. Here, the bridge heat pipe spacing was increased to 22.9 cm (9 inches) for Case 2, and the effects of a sub-cooled earth (Case 3) and a tighter temperature control system (Case 4) were examined. Approximately the same ratio of bridge surface area as for Case 1 was maintained by increasing the pipe depth into the soil to 12.2 m (40 ft) in these cases. As expected, the total heat provided per unit area is lower in Case 2 than in Case 1, due to the lower effective coupling between the bridge heat pipes and the atmosphere.

Case 3 was run to analyze the effect of a 2.8°C (5°F) cooler earth mass on system performance. Although the total energy provided by the system with the same temperature algorithm is nearly the same as for Case 2, 1.96 kwh (6694 Btu) vs 2.13 kwh (7261 Btu), the system is active for a longer time (10.33 vs 8.11 hours). However, as shown in figures 9 and 10, the design still manages to avoid preferential icing.

Table 4 Effect of Bridge Heat Pipe Spacing and Earth Heat Pipe Depth on Energy Drain -- New York City Location, March 14, 1974

Case	Bridge Pipe Spacing		Earth Pipe Depth		Q Total		Hours Active	Rate of Energy to Bridge Deck				Comments
								Total		Per Unit Area		
	cm	in.	m	ft	kwh	Btu		watt	(Btu/hr)	w/m^2	Btu/hr-ft^2	
1	15.24	6	9.1	30	2.0	6840	6.02	332	1136	179	56.8	————————
2	22.9	9	12.2	40	2.1	7261	8.11	262	895	93.9	29.8	————————
3	22.9	9	12.2	40	1.96	6694	10.33	189	648	68.0	21.6	Earth Cooled 2.8°C (5°F)
4	22.9	9	12.2	40	2.05	6980	7.62	268	916	96.1	30.5	Logic Temperature Spread Reduced
5	22.9	9	9.1	30	2.01	6869	9.6	209	715	74.9	23.8	————————
6	22.9	9	9.1	30	1.87	6383	13.33	140	478	50.1	15.9	Earth Cooled 2.8°C (5°F)
7	22.9	9	9.1	30	1.87	6395	8.62	217	742	77.8	24.7	Logic Temperature Spread Reduced

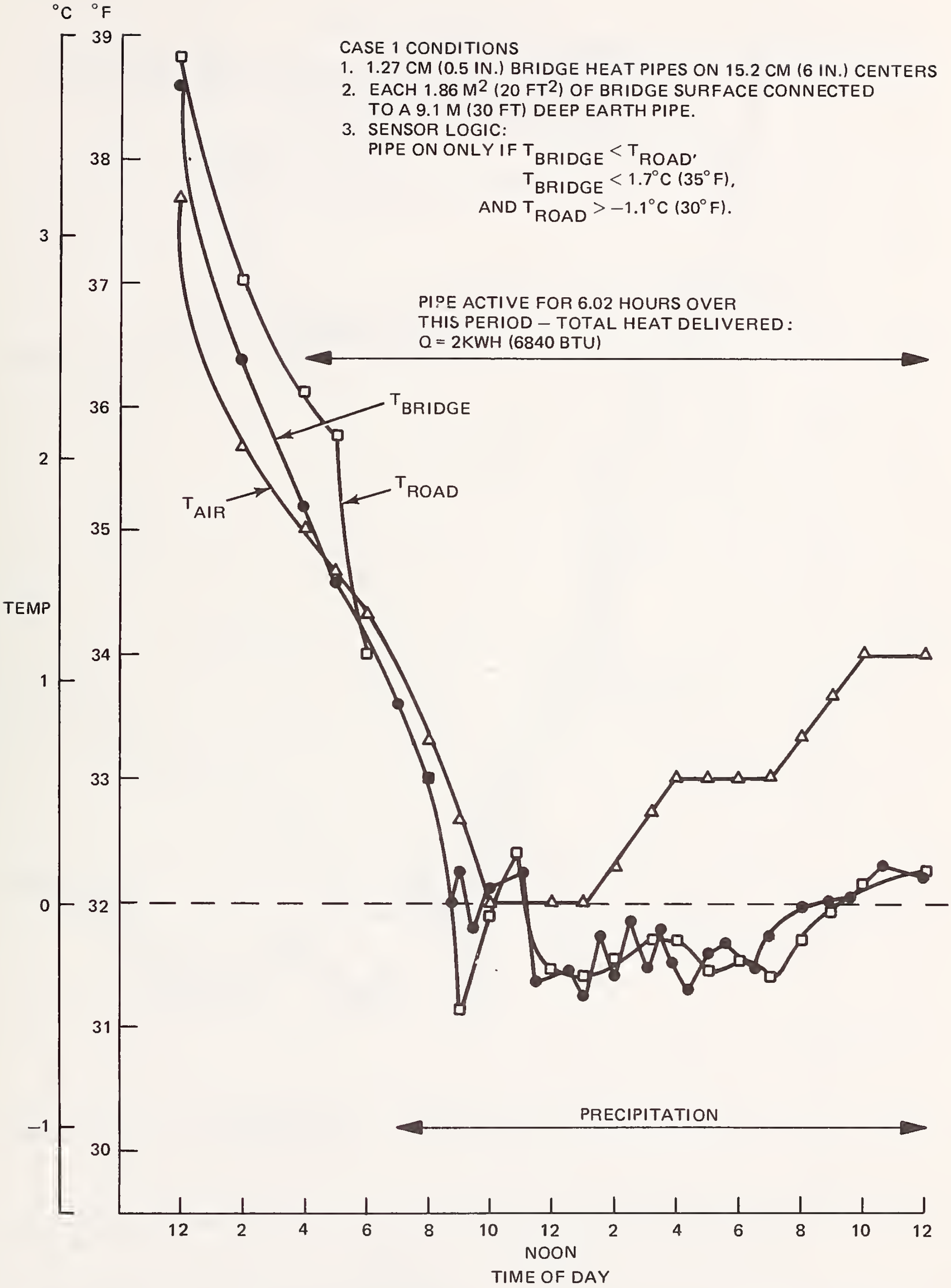


Figure 8 New York City bridge and adjacent highway transient temperatures – March 14, 1975, Case 1

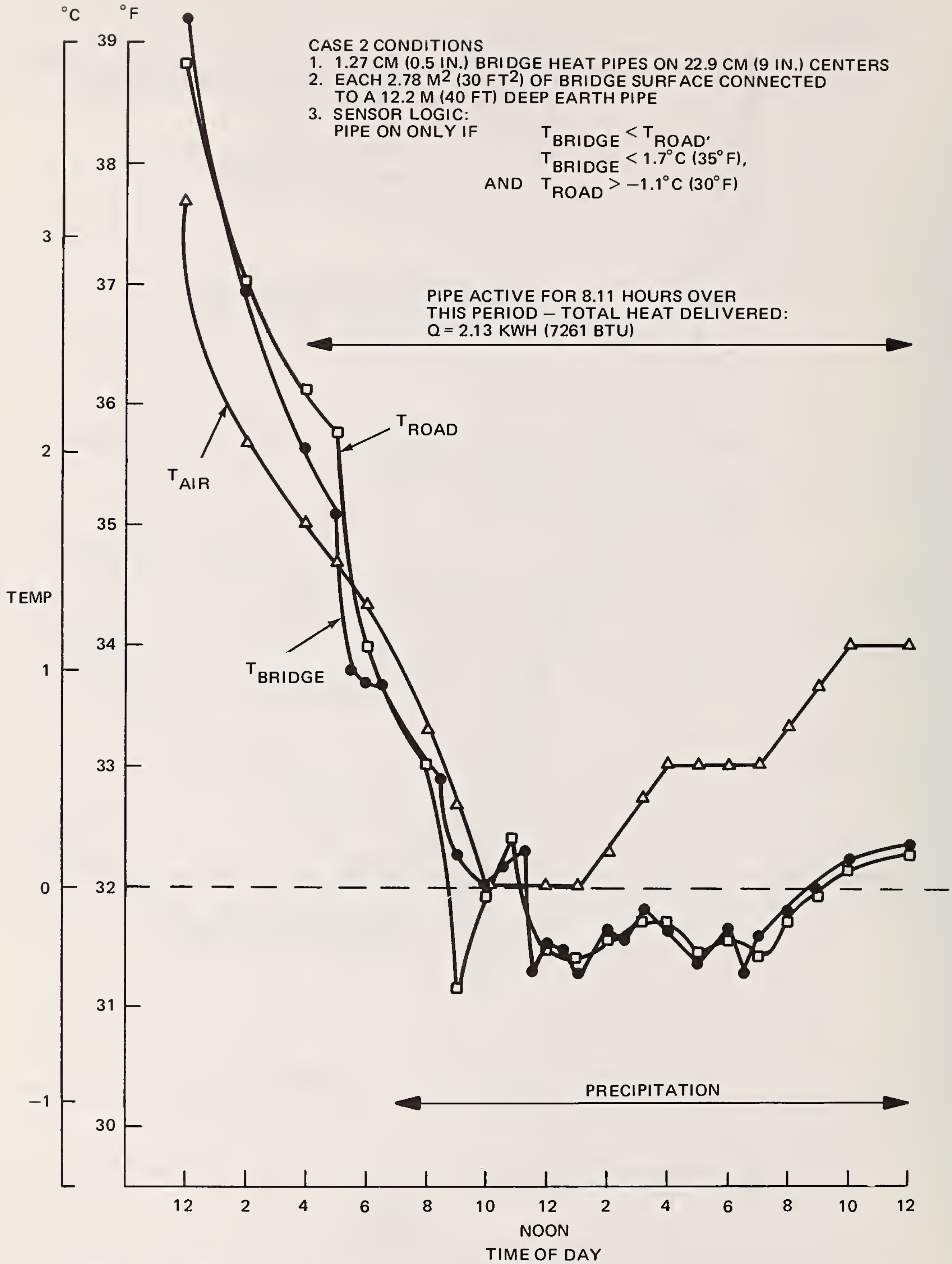


Figure 9 New York City bridge and adjacent highway transient temperatures – March 14, 1975, Case 2

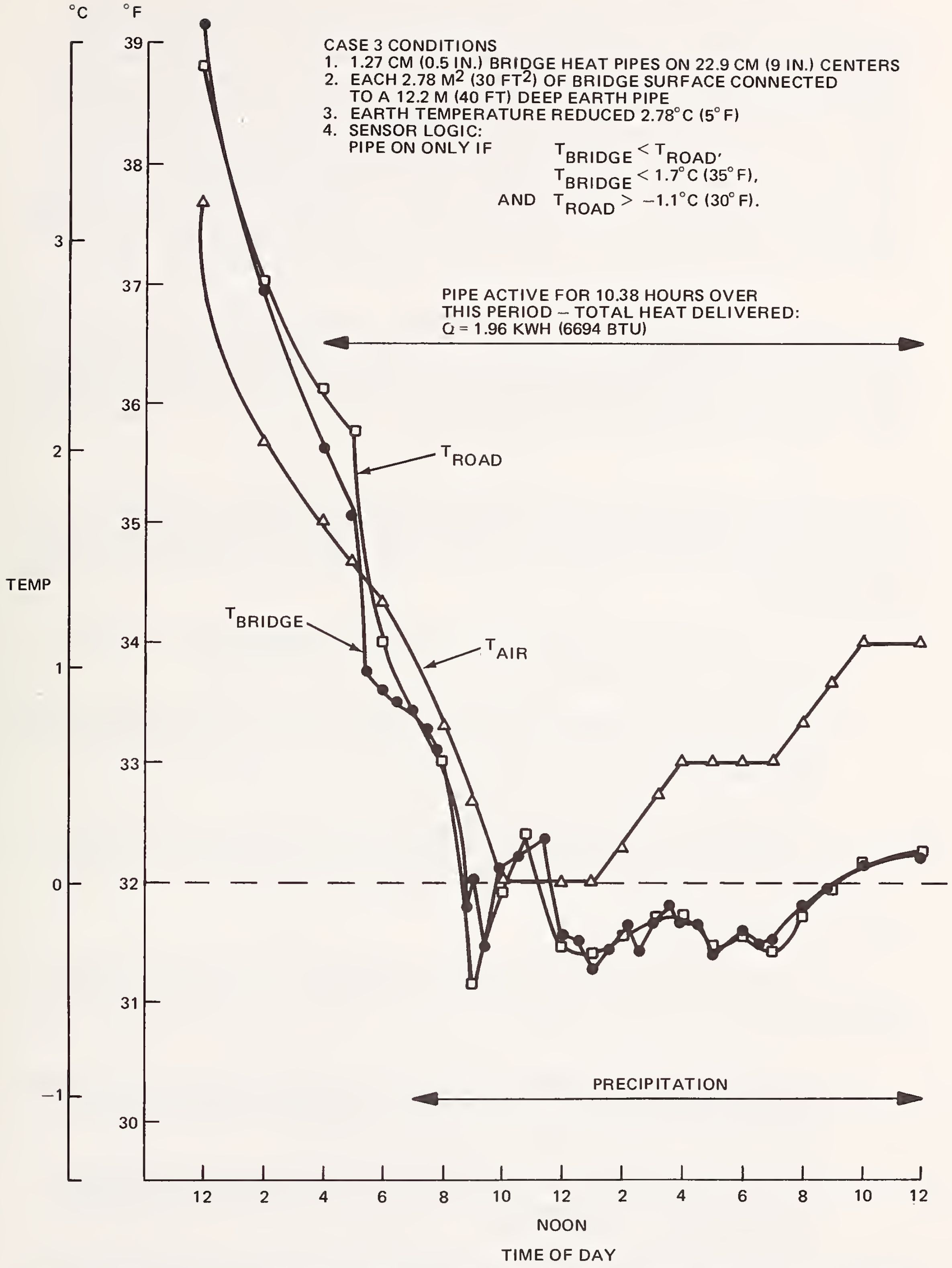


Figure 10 New York City bridge and adjacent highway transient temperatures – March 14, 1975, Case 3

The control logic in each of the described cases activates the system whenever the bridge deck temperature is less than 1.7°C (35°F) but greater than -1.1°C (30°F), and lower than the adjacent roadway. By reducing these temperature limits to 0.6°C (33°F) and -0.6°C (31°F), respectively (Case 4), the system active time is reduced slightly from 8.11 to 7.62 hours. Here again, the total energy required is essentially a constant 2.05 kwh (6980 BTU) vs 2.13 kwh (7261 Btu), and the design successfully prevents preferential icing, figure 11. Based on this slight improvement it may not be worthwhile to increase the sensitivity of the control system. However, these cases verify that the bridge heat pipe spacing can be increased to 23 cm (9 inches) and still not require that the system be active over the entire precipitation period.

Cases 5 through 7, figures 12 through 14, repeat the analyses for 9.1 m (30 ft) deep earth heat pipes: a bridge deck surface to earth heat pipe depth ratio of 929 cm^2 (1 ft^2) of surface per 30.48 cm (1 ft) of heat pipe. Since the effective coupling between the earth and the bridge has been reduced in these runs, the total energy provided is slightly less than before. Here again, each design manages to prevent preferential icing.

These results show that as long as system temperature drops are minimized across heat pipe joints and the earth heat pipes are spaced so that the earth is not allowed to cool excessively (more than 2.78°C), an earth heat pipe system of the following design can be used to avoid preferential icing for New York City:

- 1.27 cm (0.5 in.) OD bridge heat pipes installed on 23 cm (9 inch) centers at the midplane of the 19.03 cm (7.5 inch) slab

- 5 cm (2 inch) OD earth heat pipes coupled to the bridge deck such that each 0.30 square metre of deck is coupled to one metre of earth heat pipe

- Temperature control logic that activates the system whenever the bridge deck temperature is less than 0.6°C (33°F) but greater than -0.6°C (31°F), and lower than the adjacent roadway.

2.4.2.2 Oklahoma City

A review of the average weather data recorded over a 30 year period, Reference 4, indicated that Oklahoma City is a less severe icing location than New York City:

- Oklahoma City experiences about half as many rain days over the five winter months as New York, between 20 and 30 percent less total precipitation, and about 50 percent less snow

- The average monthly air temperature in Oklahoma City throughout the five winter months is from 1.6 to 6.1°C (3 to 11°F) higher than in New York

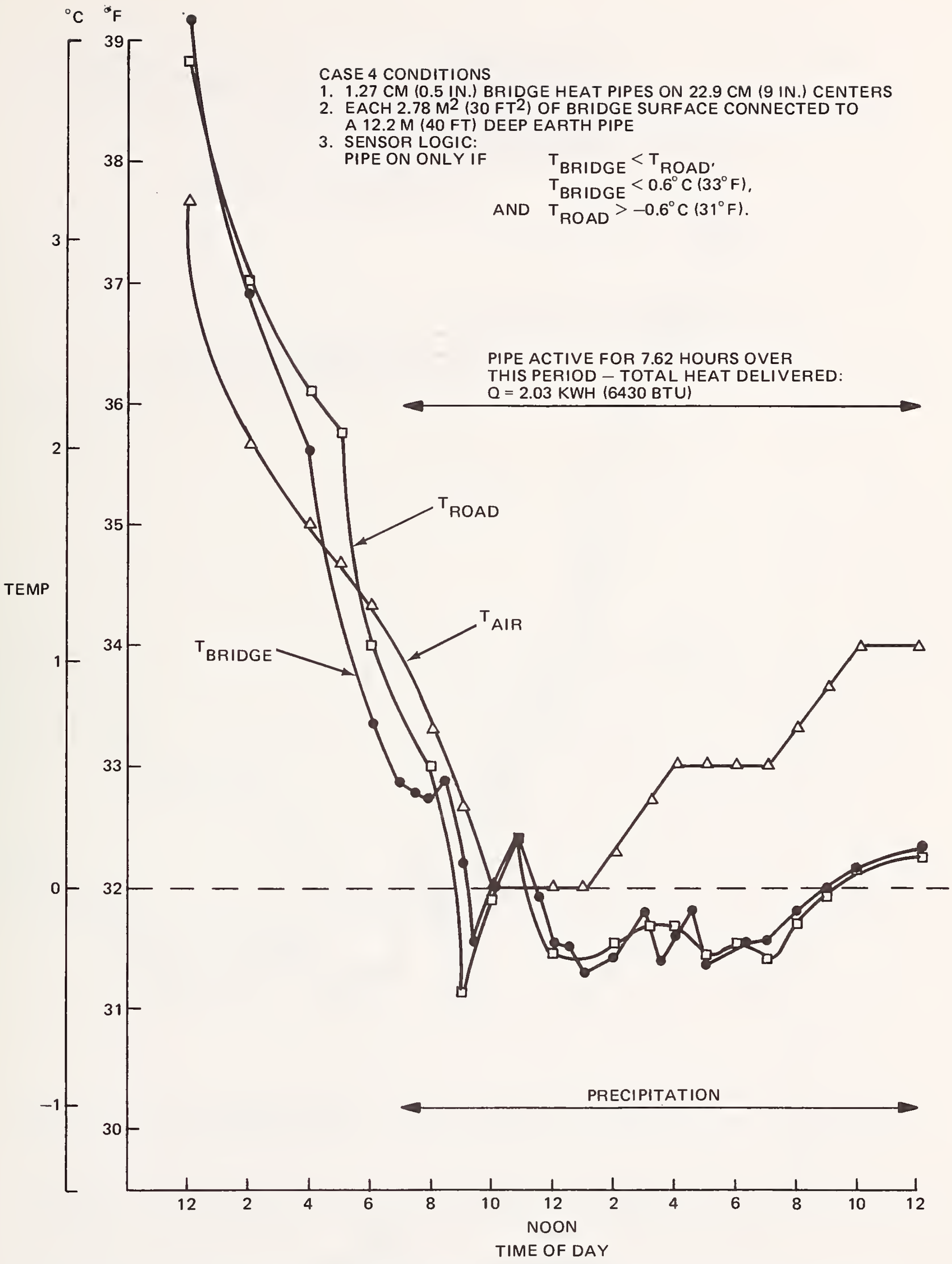


Figure 11 New York City bridge and adjacent highway transient temperatures – March 14, 1975, Case 4

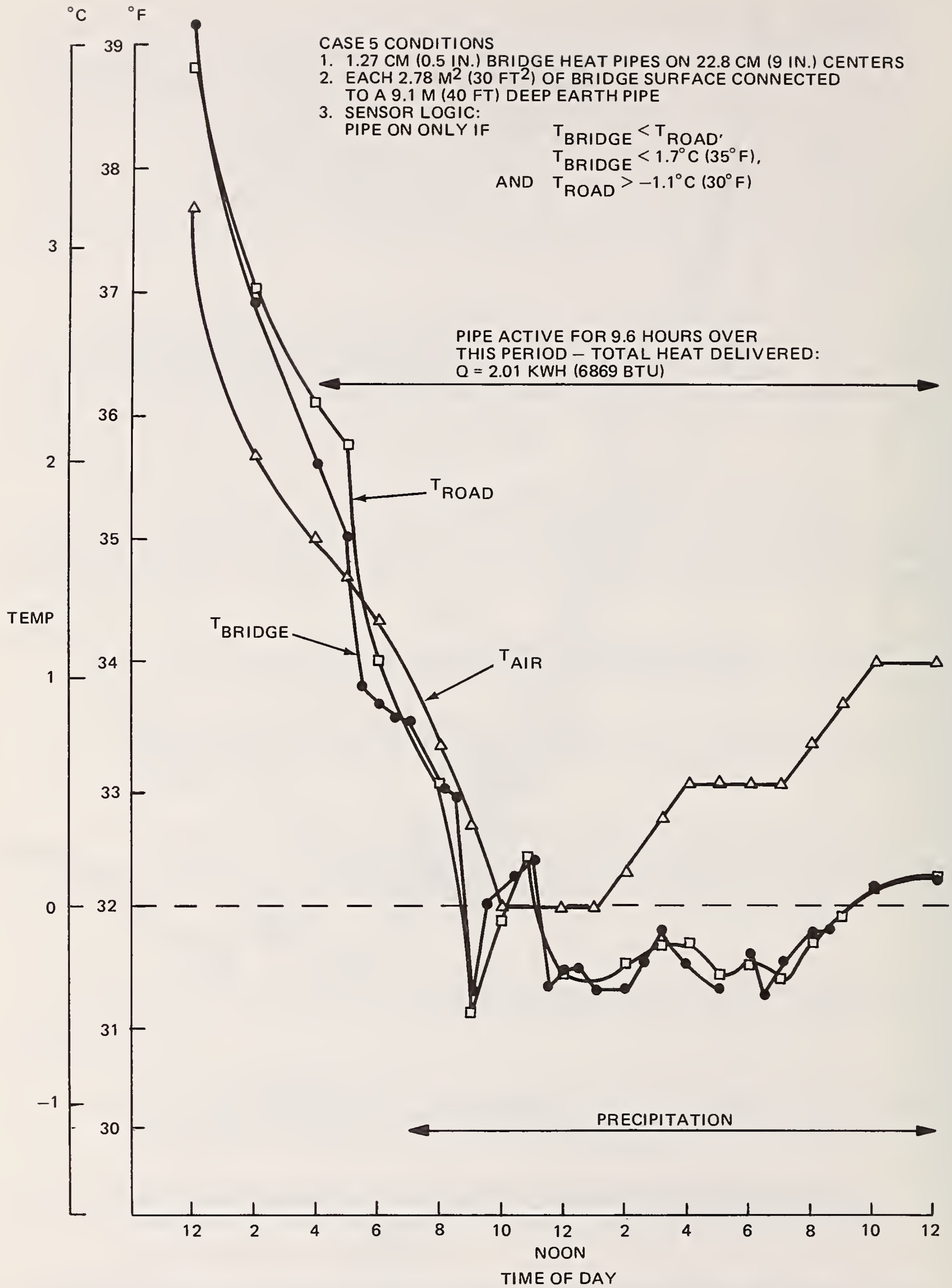


Figure 12 New York City bridge and adjacent highway transient temperatures – March 14, 1975, Case 5

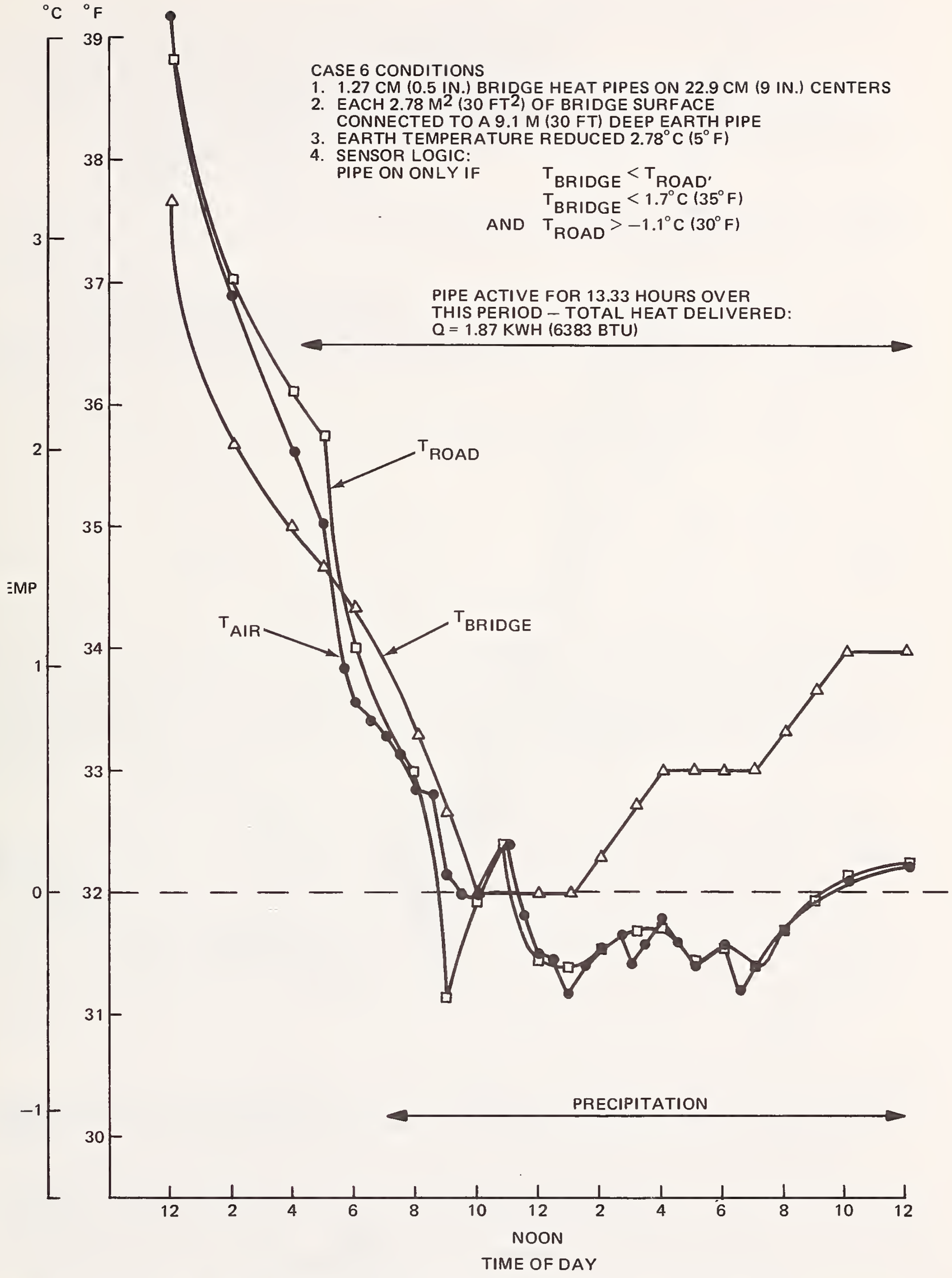


Figure 13 New York City bridge and adjacent highway transient temperatures — March 14, 1975, Case 6

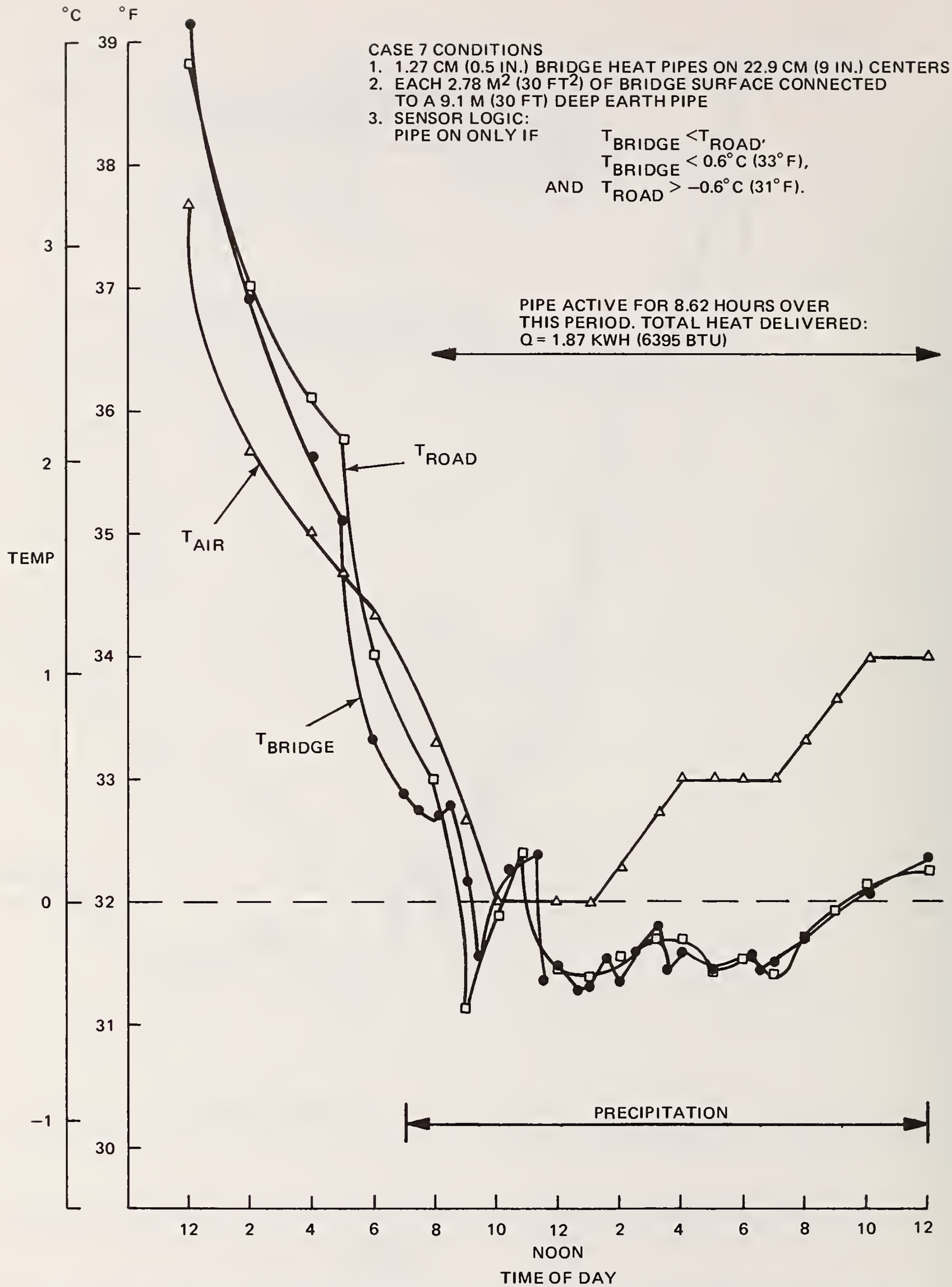


Figure 14 New York City bridge and adjacent highway transient temperatures — March 14, 1975, Case 7

- Oklahoma has an average of 30 fewer days, each year, during which the air temperature drops below freezing

- The daily variation in air temperature, from maximum to minimum, is greater in Oklahoma City than New York; this suggests that the time periods in which temperature is around 0°C (32°F) are likely to be shorter.

As a result of these facts, it is likely that less energy (and less earth volume) would be required to avoid preferential icing in Oklahoma City than in New York City.

Based on a review of Oklahoma City weather data, precipitation appears to be the most likely cause of preferential icing. For this analysis, therefore, the temperature control algorithm previously established for New York was used:

- Pipe off only if at least one of the following conditions exists:

$$T_{bridge} > T_{road},$$

$$T_{bridge} > 1.7°C\ (35°F),$$

or, $$T_{road} < 1.1°C\ (30°F).$$

Weather conditions recorded over the 1974-1975 winter were reviewed to select cases (days) for analysis. Based on this review, two days were chosen: February 22 and March 28. On each of these days the air temperature dropped below freezing and precipitation fell. Tables 5 and 6 summarize the weather conditions used in the evaluation for each day.

As shown in figure 15, for about one hour on February 22, the bridge deck could be frozen while the adjacent roadway is not, if the heat pipe system is not included. On March 28, figure 16, the bridge deck and adjacent roadway cool down nearly coincidentally, and the analysis shows that little, if any, preferential icing would occur. Based on results of the New York City analysis, this de-icing system uses 1.27 cm (0.5 inch) OD heat pipes inserted at the slab mid-plane on 23 cm (9 inch) centers. These heat pipes are coupled to 5 cm (2 inch) OD earth heat pipes in such a manner that each linear metre of earth heat pipe is connected to 0.3 square metre of bridge deck.

The system performance analysis for February 22, figure 17, shows that the heat pipe system would cause the bridge deck surface to cool down like the adjacent roadway, with both reaching the freezing point at about the same time (8:50 A.M.). As previously discussed, if precipitation is falling and the surface temperature is between 0.6 and 0.39°C (33 and 31.3°F), the model assumes that the precipitation is frozen and extracts energy from the surface to melt the precipitate (latent heat). The treatment is responsible for the sudden increase in both the bridge and roadway surface temperature noted at 9:00 A.M.

Table 5 Oklahoma City Weather Conditions, February 27, 1975

Time, hr	Air Temperature		Wind Speed, knots	Cloud Cover, Tenths	Precipitation	
	°C	°F			cm/hr	in./hr
12	5.5	42	18	10	0	0
3	3.9	39	20	10	0.152	0.06
6	1.7	35	30	10	0.305	0.12
9	0.6	33	28	10	Trace	Trace
12 Noon	0	32	21	10	0	0
3	-1.1	30	28	10	Trace	Trace
6	-1.1	30	26	10	0.051	0.02
9	-1.1	30	20	10	0	0
12	-1.1	30	20	10	0	0
Note: No significant solar energy was recorded on this day.						

Table 6 Oklahoma City Weather Conditions, March 28, 1975

Time, hr	Air Temperature		Wind Speed, knots	Cloud Cover, Tenths	Precipitation	
	°C	°F			cm/hr	in./hr
12	6.7	44	24	6	0	0
3	3.9	39	21	10	0.025	0.01
6	-0.6	31	23	10	0.025	0.01
9	-2.2	28	16	10	0.025	0.01
12 Noon	-1.7	29	18	10	Trace	Trace
3	0	32	17	10	0	0
6	1.7	35	14	10	0	0
9	1.7	35	15	10	0	0
Note: No significant solar energy was recorded on this day.						

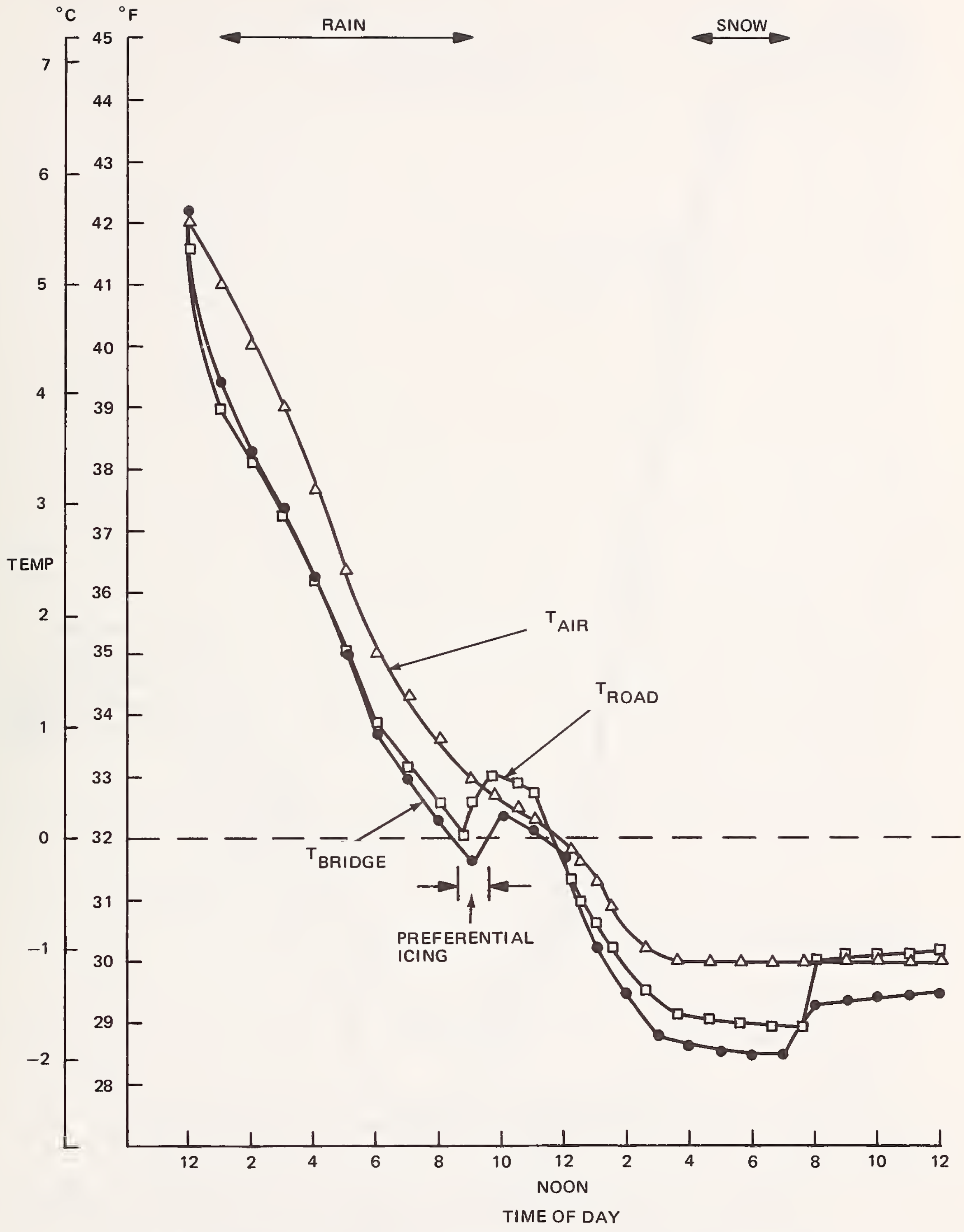


Figure 15 Oklahoma City bridge and adjacent highway transient temperatures without de-icing system – February 22, 1975

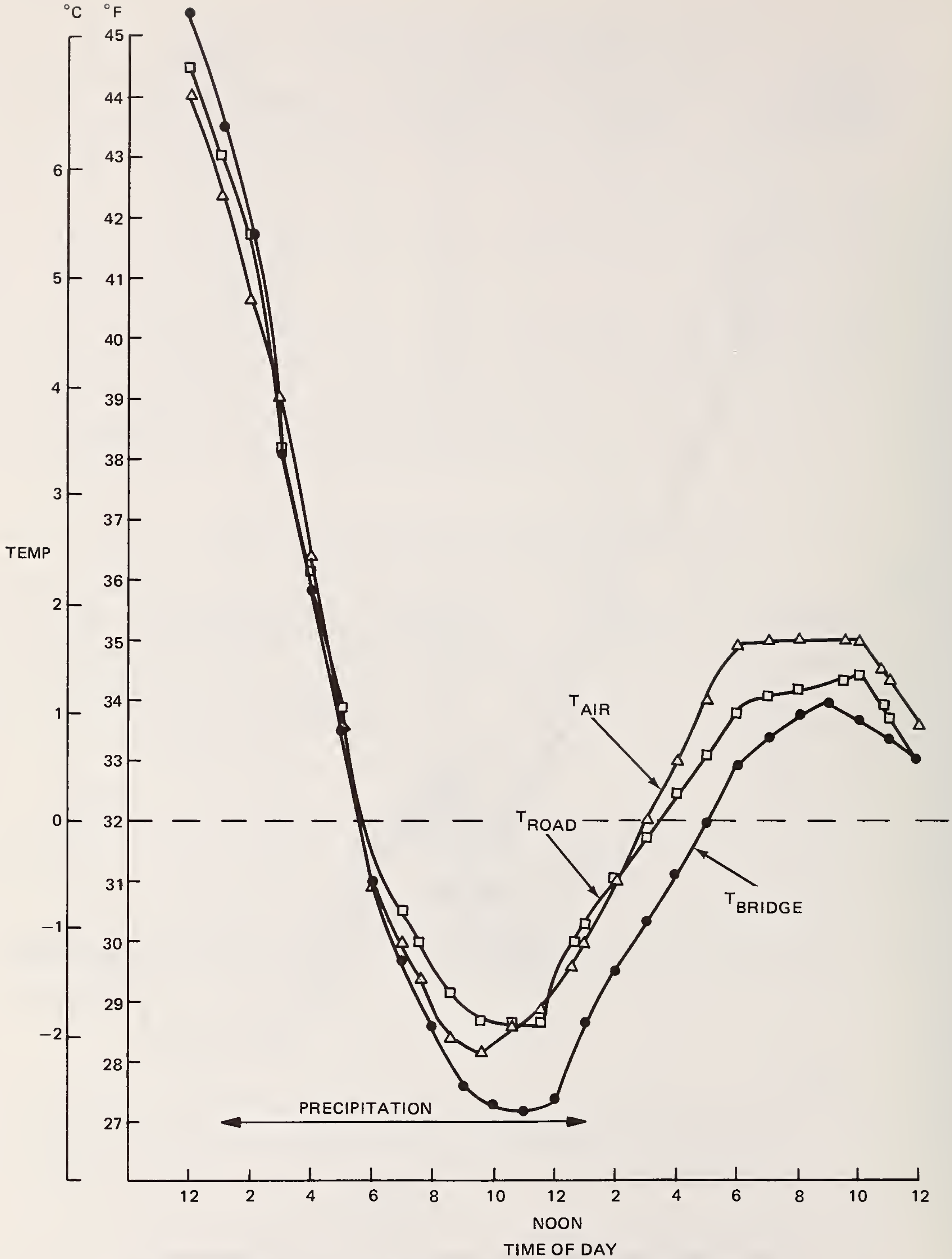


Figure 16 Oklahoma City bridge and adjacent highway transient temperatures without de-icing system — March 28, 1975

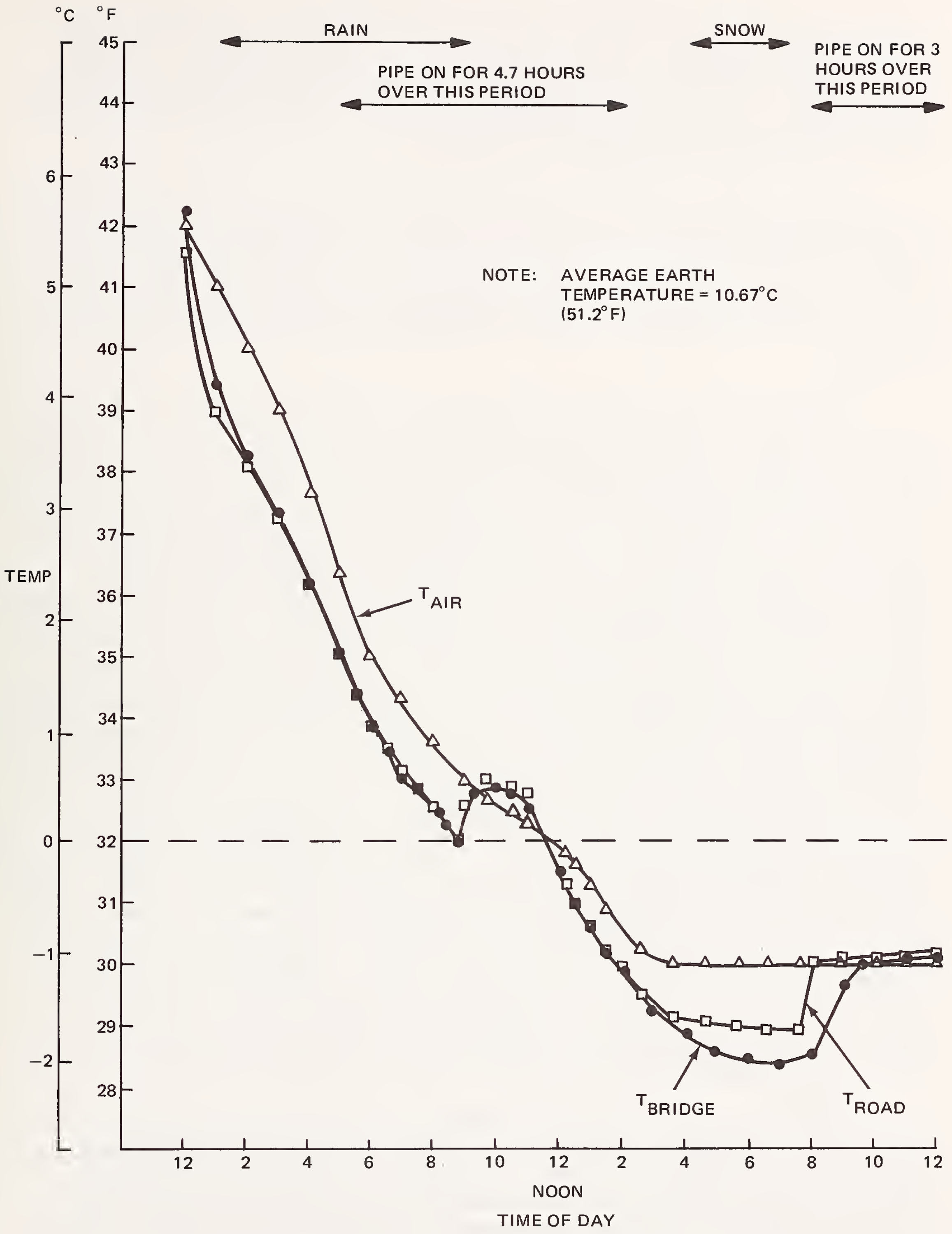


Figure 17 Oklahoma City bridge and adjacent highway transient temperatures with heat pipe de-icing system — February 22, 1975, Case 1

At this time, the rain stopped and the model stopped extracting latent energy from the surfaces. Both surface temperatures thus increased about 0.55°C (1°F) while the thermal gradients beneath the surfaces adjusted to the lower rate of energy withdrawal. The continuing drop of the air temperature caused both the bridge and roadway surface temperatures to drop below freezing almost simultaneously, at about 11:30 A.M.

Since the energy removed by the earth heat pipe may cause the earth temperature profile to be lower than predicted, the analysis for February 22 was re-run with a 2.78°C (5°F) lower average earth temperature; this corresponds to an average bulk earth temperature of 7.8°C rather than 10.67°C (46.2° rather than 51.2°F). Figure 18 presents the results of this analysis. As shown, the lower earth temperature has little effect on the system performance.

On March 28, rain changes into snow as the temperature drops from over 4.4°C (40°F) to below freezing during the morning hours. Since we would expect the earth to be sub-cooled by late spring, this analysis was performed with an average earth temperature of 10.7°C (46.2°F). Here again, as shown in figure 19, the heat pipe system is capable of preventing preferential freezing of the highway bridge deck. The deck surface temperature follows that of the adjacent roadway closely, with both reaching the freezing point at about 5:40 A.M. Traffic conditions will have a significant effect on the accumulation of snow, with heavy traffic helping to prevent the buildup of snow on the surface. When the bridge or road surface temperatures drop below 0°C (32°F), the model assumes that the precipitation freezes and accumulates as ice or snow. When the surface temperature rises to the freezing point, the accumulated ice or snow melts at a rate determined by the amount of heat which moves into the surface nodes from the interior of the bridge or earth. The surface is held at 0°C (32°F) until the entire snow layer is melted. This treatment does not take into account snow removal due to wind or maintenance, nor has provision been made for variations in the surface to atmospheric thermal coupling resulting from the snow layer. These simplifications are conservative, since they result in a thicker ice (snow) layer than would actually occur. The model assumes that the full thickness of the fallen snow must be melted, and neglects the added resistance caused by the snow, which would act as thermal insulation between the surface and the atmosphere. Ignoring this resistance results in greater heat losses through the surface than would, in fact, occur. The sensible energy required to heat the sub-cooled snow from below 0°C (32°F) to 0°C (32°F) is neglected, since it is a very small quantity compared to the energy required to melt the snow.

Table 7 presents a summary of the daily energy requirements for each of the cases. As shown in the table, the colder average earth temperature requires that the system be active for a longer period than for the warmer case, and, since an effectively lower source temperature is connected via the system to the atmosphere, less energy is drained from the earth. This analysis thus again verifies the ability of the heat pipe design to avoid preferential icing for typical severe events (days).

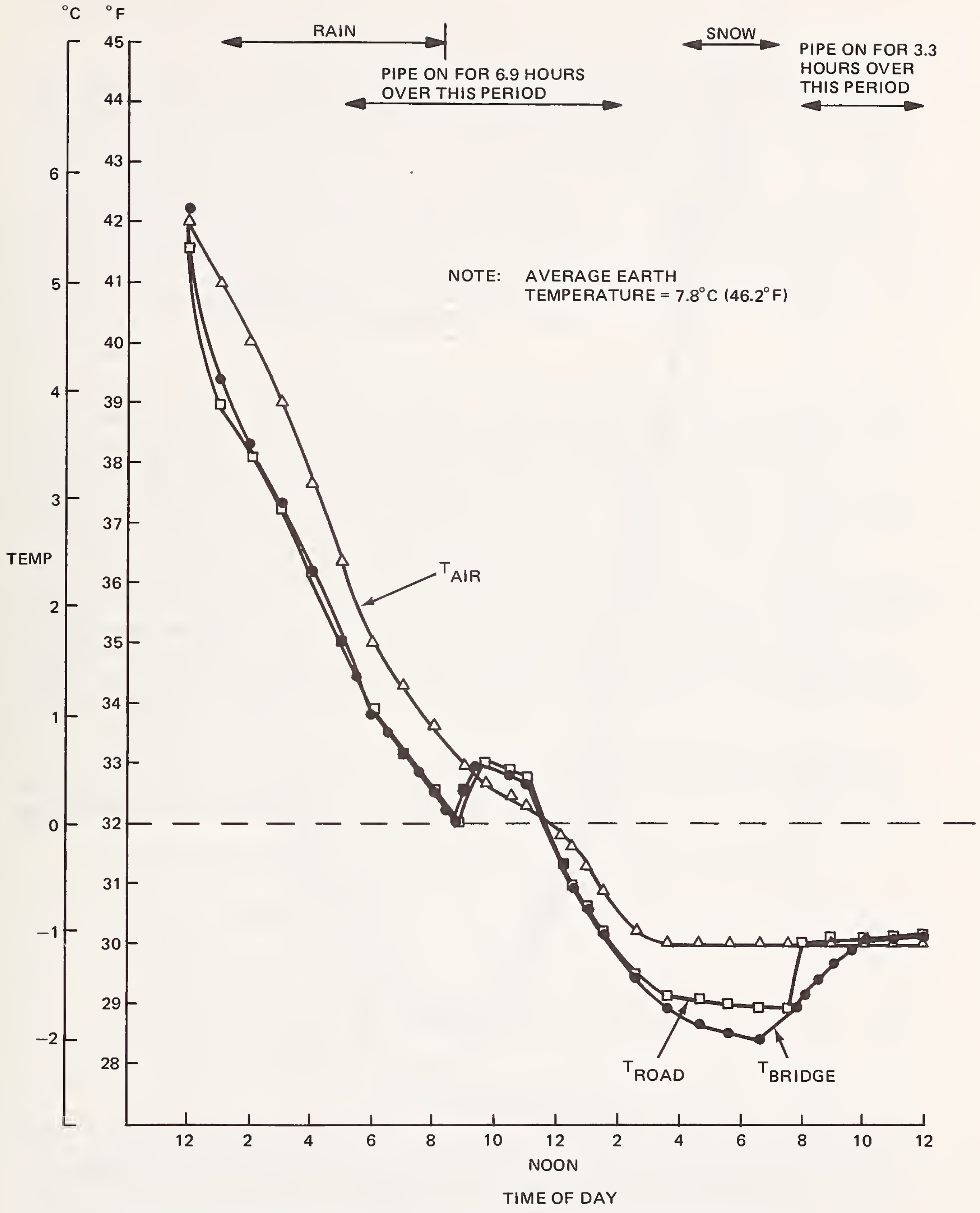


Figure 18 Oklahoma City bridge and adjacent highway transient temperatures with heat pipe de-icing system — February 22, 1975, Case 2

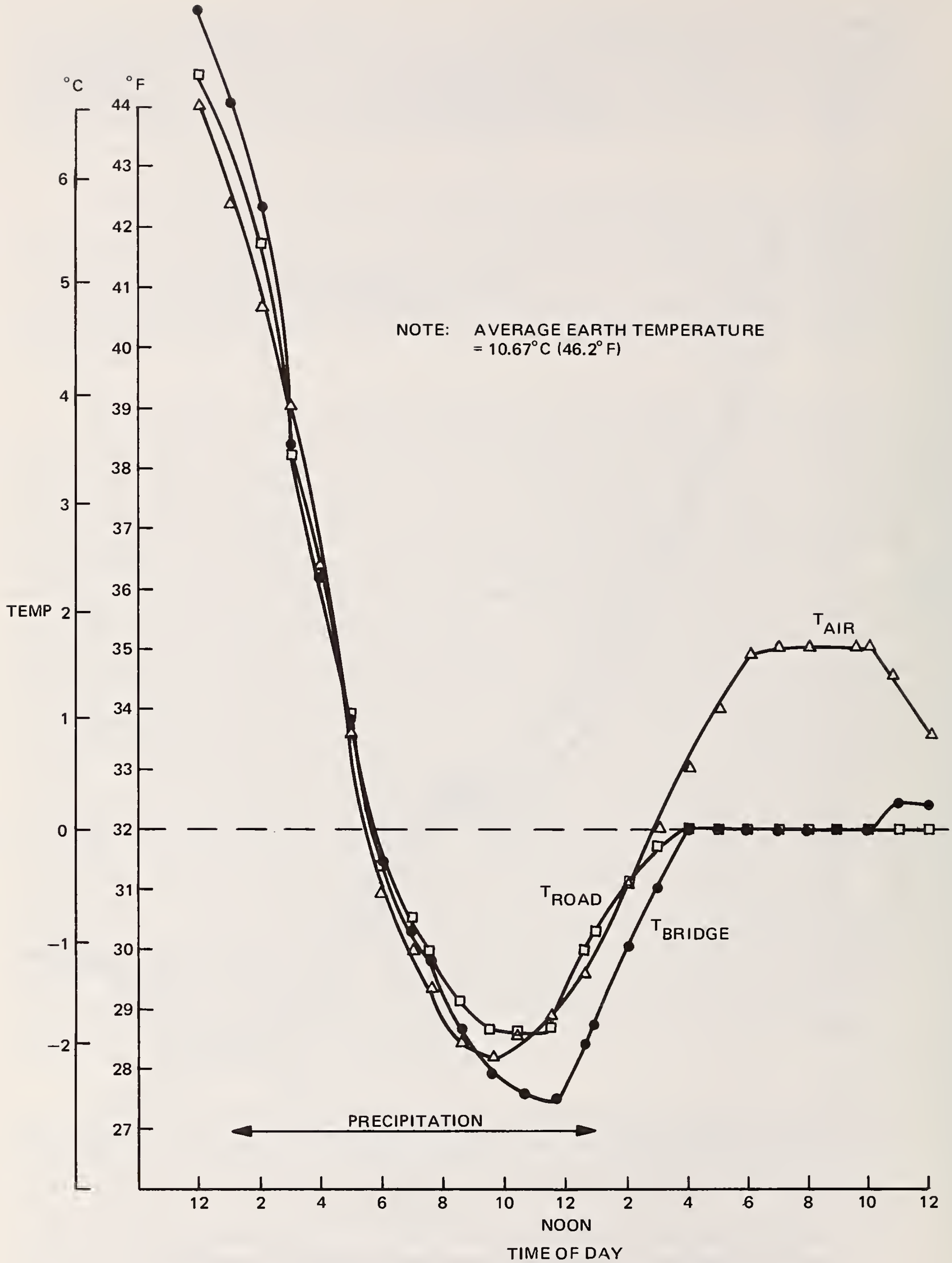


Figure 19 Oklahoma City bridge and adjacent highway transient temperatures with heat pipe de-icing system — March 28, 1975

2.4.2.3 Fresno, California

Unlike New York City and Oklahoma City, weather conditions in the non-mountain regions of coastal California rarely produce preferential bridge icing as a result of precipitation. A review of weather data for Los Angeles, San Francisco, and Fresno failed to identify any possible icing event of this type last winter (or in any of the previous six winters in Fresno). However, icing can and does occur a few times each year as a result of direct condensation (frost) on the bridge surface, Reference 5. A dew point temperature below freezing in conjunction with radiation losses from the surface of the bridge deck cools the surface deck below the dew point, and can cause moisture in the air to condense as frost. As this icing condition occurs when no precipitation is falling and the adjacent roadway is dry, it is not expected by the motorist.

Since icing occurs, in this case, without prior presence of liquid water on the surface, the use of an ordinary moisture sensor in the system control logic is useless. Moreover, since a minimum road surface temperature for pipe shut-off cannot be specified, the system would have to be left active whenever the temperature dropped below freezing, if only temperature sensors were used; this would result in a great amount of wasted energy. Although ice detectors are available, none of those studied have been found to be capable of detecting ice reliably under these circumstances. As an alternate approach, the atmospheric dew point can be measured and compared with the bridge surface temperature. Such a system would be activated whenever the bridge temperature was below freezing and approaching the dew point, but would be inactive when surface temperature was more than a few degrees above the dew point temperature, even if it were below freezing.

Analyses were performed to evaluate system performance using temperature probes on both the bridge and adjacent roadway surfaces and a dew point sensor. The following control logic was used:

Pipe off only if at least one of the following conditions exists:

$T_{bridge} > T_{road}$,

$T_{bridge} > 0.6°C\ (33°F)$,

$T_{bridge} > \text{Dew Point Temperature} + 1.6°C\ (3°F)$,

or $T_{road} < 0°C\ (32°F)$

The system becomes active at 1.6°C (3°F) above the dew point temperature to allow for transient effects during startup. Here again, the design assumes that 1.27 cm (0.5 inch) OD heat pipes are embedded at the bridge mid-plane, 8.9 cm (3.5 inch) below the surface, on 23 cm (9 inch) centers, and are connected to 5 cm (2 inch) OD earth heat pipes such that each linear metre of the earth pipes is connected to 0.3 square metre of deck surface.

In keeping with our analytical procedure, recorded weather data were reviewed to select cases (days) for analysis. The two days selected were January 5 and 6, 1970. The weather conditions recorded and input in the model for each of these days are presented in table 8.

The analyses presented in figures 20 and 21 were performed without the heat pipe system to demonstrate that preferential icing would have occurred on the selected days. Based on weather data recorded over a 30-year period, the average annual atmospheric temperature will be 16°C (60.8°F) for this site, Reference 3. At a depth of about 25 feet into the earth, therefore, the soil should be at a temperature of 15 to 16°C (60 to 61°F) throughout the year. In order to include the effect of the natural thermal gradient in the soil, the analysis was run using the temperature profile shown in figure 3.

As shown in figures 20 and 21, the analysis predicted that preferential icing (bridge temperature below both freezing and the dew point) would occur for 1.8 hours on both January 5 and 6. Since a literature search of actual recorded events indicates considerably shorter periods of preferential icing (on the order of 15 to 20 minutes), the analysis may be conservative. Specifically, since the radiative coupling to the atmosphere is based on empirical correlations, the analysis may overestimate this thermal condition.

Analytical results for the heat pipe system are summarized in table 9 and figures 22 and 23. As shown in the figures, the earth heat pipe system successfully prevents preferential icing on both days. On January 5 the system is active for 3.4 hours and provides 0.852 kwh (2910 Btu) to the 2.78 m^2 (30 ft^2) bridge section analyzed, or 0.089 kw/m^2 (28.5 $Btu/hr\text{-}ft^2$). On January 6 the system is active for 4.1 hours and provides 1.18 kwh (4027 Btu) to the bridge section, or 0.103 kw/m^2 (32.7 $Btu/hr\text{-}ft^2$). The greater energy demand on January 6 is the result of a lower deck temperature which provides more potential for heat flow.

2.4.3 Conclusions: Earth Heat Pipe System Verification

The analyses performed for New York City, Oklahoma City, and Fresno verified that the same design can be used to avoid preferential icing in all three locations. That is, a system based on the use of 5 cm (2 inch) OD earth heat pipes coupled via 5 cm (2 inch) OD headers, to 1.27 cm (0.5 inch) OD bridge heat pipes on 23 cm (9 inch) centers at the slab midplane such that each linear metre of earth pipe is provided for each 0.30 square metre of deck surface area can eliminate preferential icing for selected worst-case events. However, a serious problem indicated by these evaluations is the critical importance of the following four parameters:

- The thermal coupling between the earth heat pipes and the earth, which affects the ability of the system to provide energy at the rate required to avoid preferential icing

Table 7 Energy Requirements for Oklahoma City Heat Pipe Bridge De-Icing System

1975 Date	Energy Reqmts*		Energy Rqmts* Per Area		Hours System Active	Avg Energy Rate		Avg Earth Temp	
	kwh	Btu	kwh/m^2	Btu/ft^2		kw/m^2	Btu/hr-ft^2	°C	°F
2/22	1.614	5509	0.556	176.6	7.3	0.076	24.2	10.66	51.2
2/22	1.511	5158	0.541	171.9	10.17	0.053	16.9	7.89	46.2
3/28	1.699	5800	0.608	193.3	11.0	0.553	17.57	7.89	46.2

*For 2.78 m^2 (30 ft^2) of bridge surface

Table 8 Fresno, California Weather Conditions, January 5-6, 1970

Date	Time, hour	Air Temperature		Dew Point		Cloud Coverage, Tenths	Wind, knots	Weather
		°C	°F	°C	°F			
1/5	1 AM	-0.6	31	-0.6	31	10	3	Fog
	4 AM	-2.2	28	-2.2	28	10	0	Fog
	7 AM	-3.9	25	-3.9	25	10	3	Fog
	10 AM	0	32	-0.6	31	10	3	Ground Fog
	1 PM	7.2	45	2.8	37	7	4	Smoke, Haze
	4 PM	8.9	48	2.8	37	8	0	Smoke, Haze
	7 PM	1.7	35	0.6	33	2	0	Ground Fog
	10 PM	-0.6	31	-1.1	30	1	0	Ground Fog
1/6	1 AM	-2.2	28	-2.2	28	1	0	Ground Fog
	4 AM	-3.3	26	-3.9	25	1	5	Ground Fog
	7 AM	-3.3	26	-3.9	25	1	2	Ground Fog
	10 AM	+2.8	37	0.6	33	1	3	Ground Fog, Smoke
	1 PM	8.3	47	2.2	36	7	6	Smoke, Haze
	4 PM	11.7	53	-2.2	28	8	5	Smoke, Haze
	7 PM	5.5	42	-0.6	31	10	4	Smoke, Haze
	10 PM	1.7	35	0	32	10	2	Ground Fog, Smoke

Table 9 Energy Requirements for Fresno, California Heat Pipe Bridge De-Icing System

Date	Total Daily Energy		Demand Rate	
	w-hr/m^2	Btu/ft^2	kw/m^2	Btu/hr-ft^2
1/5	305	97	0.089	28.52
1/6	422	134	0.102	32.66

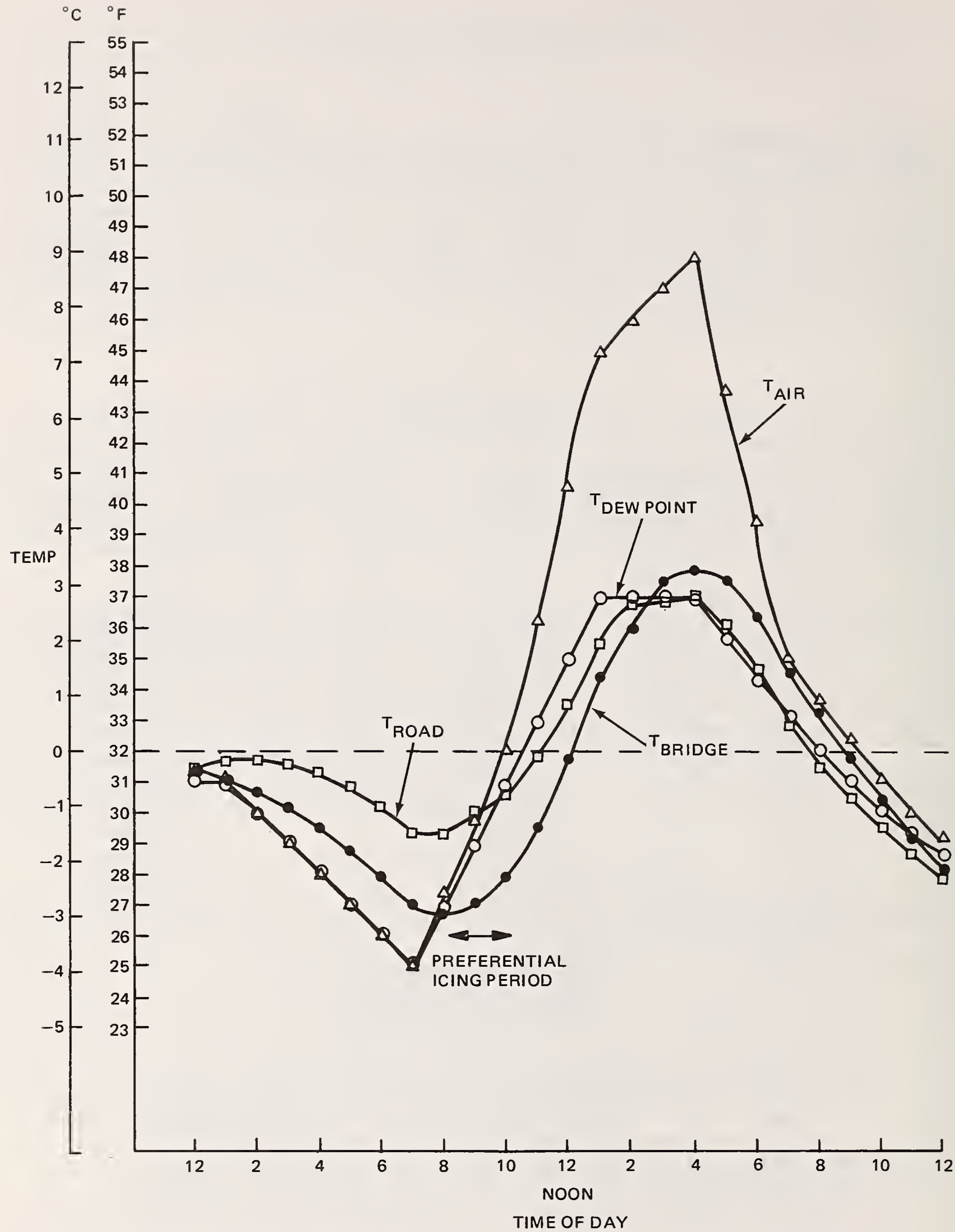


Figure 20 Fresno, California bridge and adjacent highway transient temperatures without de-icing system — January 5, 1970

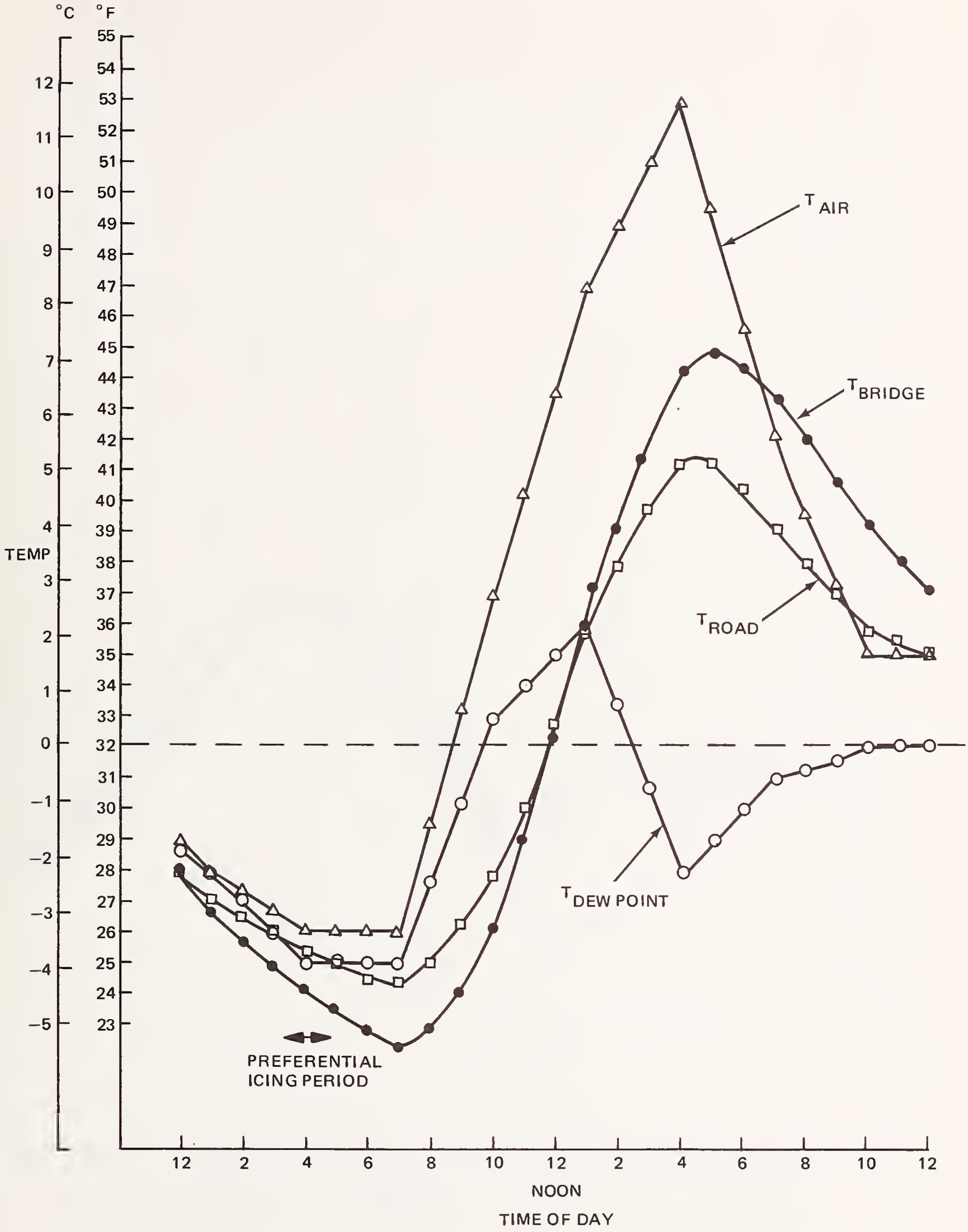


Figure 21 Fresno, California bridge and adjacent highway transient temperatures without de-icing system – January 6, 1970

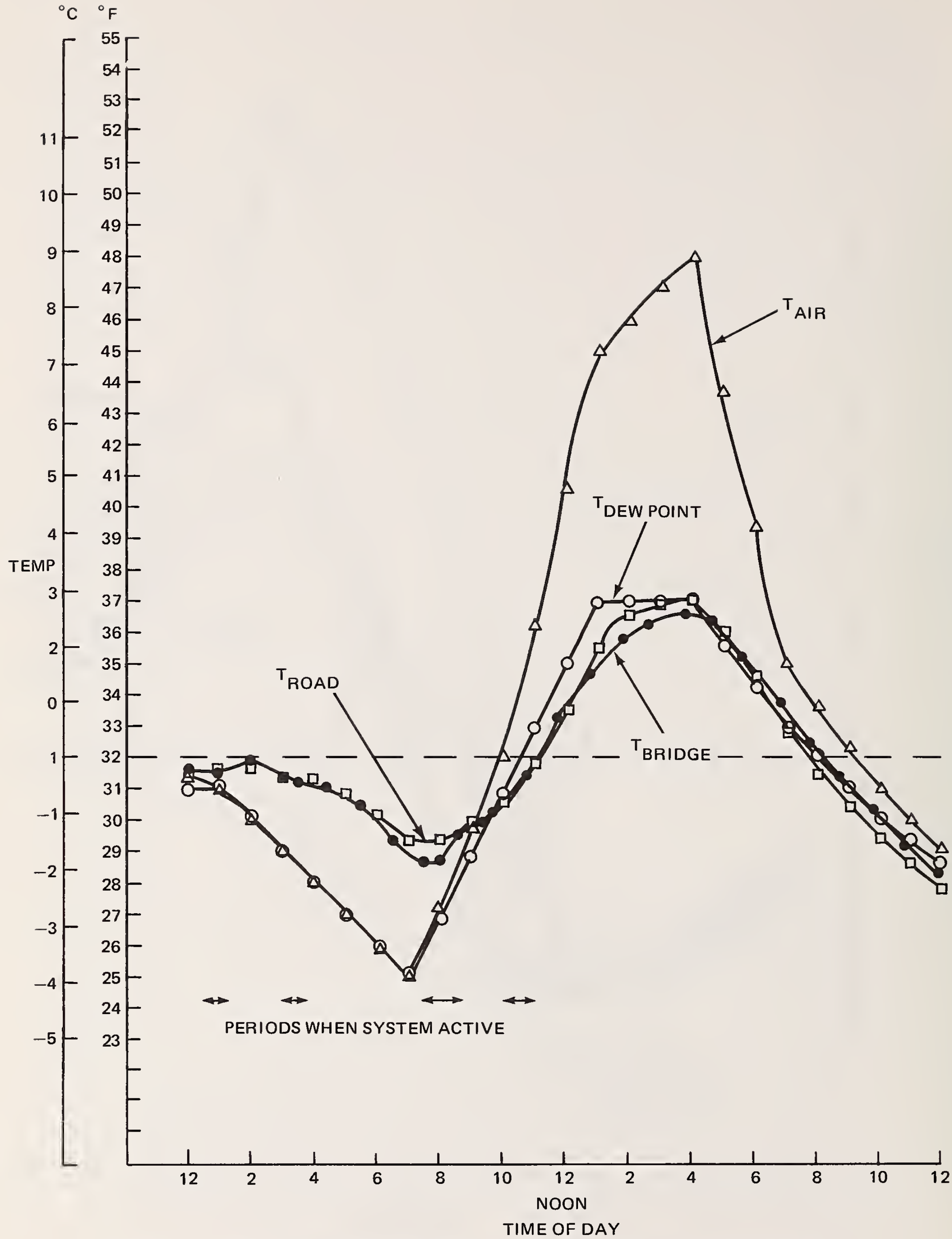


Figure 22 Fresno, California bridge and adjacent highway transient temperatures with heat pipe de-icing system – January 5, 1970

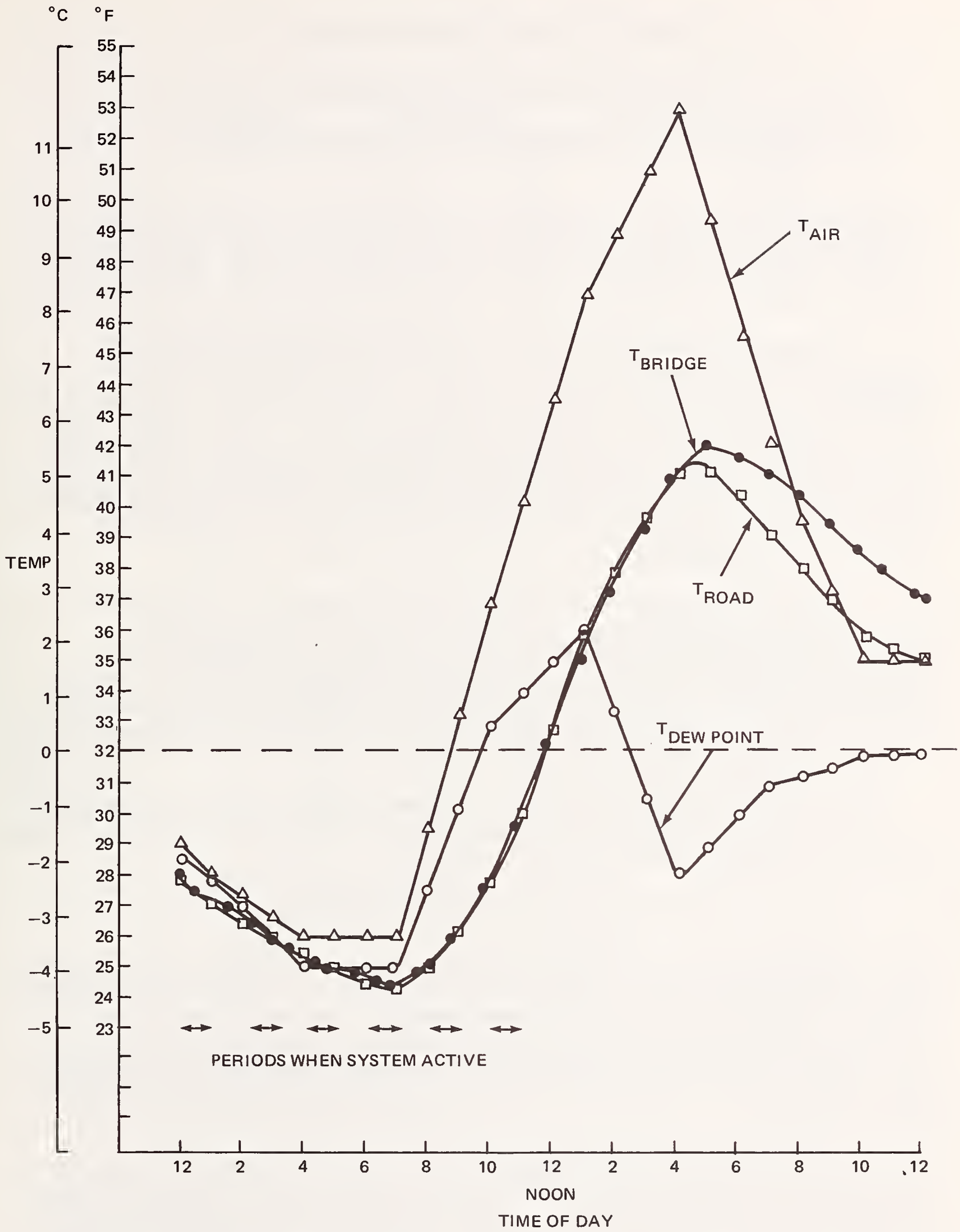


Figure 23 Fresno, California bridge and adjacent highway transient temperatures with heat pipe de-icing system – January 6, 1970

- The temperature drop across joined heat pipes
- The thermal resistance between the bridge heat pipes and the slab
- The transient performance and shutoff characteristics of a valved heat pipe.

These parameters are very important because the earth is a fairly low temperature source. Since earth temperatures have a range of only 7.2 to 15.5°C (45 to 60°F) throughout the continental United States, minimizing system temperature drops is essential to assure satisfactory performance.

Although heat pipes themselves are very efficient thermodynamic devices, which can transfer large quantities of energy (heat) with small temperature drops (on the order of a few °C), the conductances of the soil, the soil to heat pipe interface (contact), the joints between earth and header heat pipes and header and bridge heat pipes, and the interface between the bridge heat pipes and concrete slab can introduce sizeable temperature drops into the system and compromise performance. Due to the critical importance of these conductances on system operation a test program was required to measure these parameters.

Although investigators had considered the application of valved heat pipes in designs such as the one described, the performance of these devices had not yet been demonstrated. Therefore, a test program was needed to determine the ability of such a valve to thermally "disconnect" the earth from the ambient and start operation immediately after activation; that is, the time required to get the pipe to behave thermally as though the valve were not present must be measured.

Since FHWA agreed with our concerns in this area, they expanded the scope of this program to include limited testing. Subsection 2.6 describes the test plans followed, and the results achieved.

2.5 ANNUAL ENERGY/LAND-MASS REQUIREMENTS

Although the requirements of size, spacing, and number of heat pipes does not necessarily vary with location, the annual energy required, and hence the land mass required, obviously does change. The annual energy required to avoid preferential icing for each site was therefore evaluated. This evaluation was based on a review of daily climatic conditions recorded during the winter of 1974, which was judged to be a typical winter season for all of these locations.

As already described, integrated analyses were used to determine the daily energy expended, with various control systems, under different weather conditions, for each of these sites. The recorded weather conditions for the winter of 1974 then were reviewed on the basis of these data and engineering judgment, and an energy demand assigned for each winter day. The total annual energy requirements thus determined are presented in tables 10 and 11.

Table 10 Energy Rates Required to Avoid Preferential Icing

Location	*Control System Logic	Rate of Energy Required to Avoid Preferential Icing		**Typical Active Period, hr	Energy Required Per Icing Event	
		kw/m^2	Btu/hr-ft^2		kwh/m^2	Btu/ft^2
New York City	A	0.19-0.06	60-20	2-6	0.38	120
New York City	B	0.19-0.06	60-20	2-6	0.38	120
Oklahoma City	A	0.08-0.05	27-16	8-10	0.79	250
Oklahoma City	B	0.08-0.05	27-16	8-10	0.79	250
Fresno, California	C	0.095	30	3-4	0.38	120

*Control System Logic conditions: Pipe off only if:

A: $T_{bridge} > 0.6°C$ (33°F), $T_{road} < -1.1°C$ (30°F), or $T_{bridge} > T$ road

B: $T_{bridge} > 0.6°C$ (33°F), $T_{road} < -1.1°C$ (30°F), $T_{bridge} > T_{road}$ or deck is dry

C: $T_{bridge} > T$ dew point, $T_{bridge} > 0°C$ (32°F), or $T_{road} < T$ dew point and $T_{road} < 0°C$ (32°F)

**Rate varies over active period; as rate decreases, length of active period increases.

Table 11 Annual Energy/Land Required to Avoid Preferential Icing

Location	*Control System Logic	Annual Energy Required		Earth Requirements Per Bridge Area: Volume		Area	
		kwh/m^2	Btu/ft^2 bridge	m^3/m^2	ft^3/ft^2	m^2/m^2	ft^2/ft^2 bridge
New York City	A	2.20	7011	26.712	87.64	1.35	1.35
New York City	B	1.02	3225	12.28	40.31	0.62	0.62
Oklahoma City	A	1.47	4674	17.81	58.43	0.90	0.90
Oklahoma City	B	0.51	1612	6.14	20.15	0.31	0.31
Fresno, California	C	0.71	2260	8.61	28.25	0.44	0.44

*Control System Logic conditions: Pipe off only if:

A: $T_{bridge} > 0.6°C$ (33°F), $T_{road} < -1.1°C$ (30°F), or $T_{bridge} > T$ road

B: $T_{bridge} > 0.6°C$ (33°F), $T_{road} < -1.1°C$ (30°F), $T_{bridge} > T$ road, or deck is dry

C: $T_{bridge} > T$ dew point, $T_{bridge} > 0°C$ (32°F), $T_{road} < T$ dew point, or $T_{road} < 0°C$ (32°F)

**Based on allowable temperature drop of 2.78°C (5°F), earth density of 1280 kg/m^3 (80 lb/ft^3), and specific heat of 0.232 w-hr/kg-°C (0.2 Btu/hr-lb-°F)

***Based on active (heat pipe) depth of 19.8 m (65 ft)

The annual energy requirements presented in tables 10 and 11 assume use of the control systems judged to be potentially viable for the specific location. For Oklahoma City and New York City these include both a simple, temperature-only sensor system and a temperature-plus-moisture sensor system. Obviously, a moisture sensor design requires significantly less annual energy than one which uses only temperature sensors (about half as much energy for New York City and about a third as much for Oklahoma City). However, since this design will only activate the earth heat pipe system when moisture can be measured, it obviously is less reliable than the temperature-only sensor system. Even if the assumption that preferential icing occurs most frequently during periods of frozen precipitation is correct, it does occassionally occur for other events. For example, in California, frost often forms directly on a surface on a cold, clear night; under this condition the moisture sensors would not indicate the presence of water, and the system would remain inactive.

With the temperature-only sensor system, 1.35 m^2 and 0.9 m^2 of land area would be required per m^2 of bridge deck in New York City and Oklahoma City, respectively. These requirements are based on an allowable temperature drop of 2.78°C (5°F) during the winter and the use of 19.8 m (65 ft) deep earth heat pipes. Adding moisture sensors cuts these requirements considerably, to 0.6 and 0.3 m^2 of land per m^2 of bridge deck for New York City and Oklahoma City, respectively. These requirements are of particular interest since they provide some idea of the amount of adjacent land that is needed for a particular bridge. Since the land below the bridge deck is likely to be available, a requirement for an amount of land equivalent to the area of the deck should not pose a problem. These system requirements thus seem to be easy to meet for most cases.

The analyses performed for the Fresno, California site indicated that the use of the temperature-only sensor system would not prevent icing due to frost condensation, unless the bridge temperature were always prevented from falling below the temperature of the adjacent roadway. Since this would require excessive energy, a system for this site should include dew point sensors to limit the land requirements to practical limits. Such a system would require 0.4 m^2 of land area per m^2 of bridge deck.

Subroutines that have been incorporated into the computer program compute the instantaneous rate and total energy required to avoid preferential icing. The rate of energy requirements presented in table 10 are the maximum values indicated by the computer. Note that the peak value of 0.19 kw/m^2 (60 Btu/hr-ft^2) indicated for New York City corresponds exactly with the earlier hand calculations that were used to size system requirements, Reference 2. The analysis also indicated that although the rate of energy required would be less for Oklahoma City than for New York City, the total energy required per event would be about twice as great, or 0.79 kwh/m^2 for Oklahoma City vs 0.378 kwh/m^2 for New York City (250 Btu/ft^2 vs 120 Btu/ft^2) due to the longer active time period required.

2.6 CRITICAL COMPONENT HARDWARE TESTING

2.6.1 Earth Heat Pipe

The ability of the earth and earth heat pipes to fulfill both energy-rate and total-energy requirements was investigated by a test program involving four heat pipes. Two 2-inch, nominal, and two 1-inch, nominal, diameter heat pipes, each 12.2 m (40 ft) long, were produced and charged with ammonia. The pipes were instrumented with thermocouples located as shown in figure 24. In addition, offset thermocouples were set in blocks and positioned 2.54 cm (1 inch) from the pipe surface, figure 25, in order to measure the response of the soil in the immediate vicinity of the pipes. Wooden thermocouple trees were also built to measure the earth temperature at distances of 30.48 cm (1 ft) and 60.96 cm (2 ft) from the pipe, figure 26.

The pipes and thermocouple trees were inserted into the ground by a well-drilling firm. First, a hole 10.67 m (35 ft) deep was augered in the ground, figure 27. Since the loose, sandy composition of the local soil caused the holes to collapse as the auger was removed, a metal casing was hammered into the hole, figure 28. The soil in the casing was then removed and the heat pipes or trees inserted, figures 29 through 32. The casing was then removed, and the hole backfilled with earth.

Unfortunately, the drilling/insertion operation proved so difficult because of the loose, sandy soil conditions that excessive installation time was consumed and some instrumentation was damaged. For example, a 5 cm (2 inch) pipe, the first installed, had so many thermocouples destroyed that sufficient data could not be taken; the installation was thus essentially useless. Moreover, the first 2.54 cm (1 inch) pipe to be installed failed to work, apparently from loss of ammonia; the valve on the top of the pipe, which was left there for possible future tests, appeared to have suffered damage during installation.

The two remaining, working heat pipes, 5 and 2.54 cm (2 and 1 inch) in diameter, were tested by flowing chilled water over the 1.524 m (5 ft) above-ground condensers to simulate heat removal for de-icing. For this purpose, insulated metal sleeves, figure 33, were placed over the pipe condensers, figure 34. A Dunham-Bush package chiller was used to cool the water and pump it through the loop. Coolant temperature was measured at the inlet and outlet of the insulated sleeve to enable the energy flow rate to be found from the increase in water temperature. All temperature readings were taken using a Doric integrating microvoltmeter with 0°C (32°F) reference junction.

The 5 cm (2 inch) pipe was tested on two consecutive days. Cooling water at about 2 to 3.3°C (36 to 38°F) was run over the condenser for six hours on the first day, and for five hours on the second day, with the second run starting 24 hours after the first. Temperature profiles (vs time) for various soil depths are shown in figures 35 through 37. As shown in these figures, temperatures at the 30.48 cm (1 ft) radius changed very little. (This is in agreement with

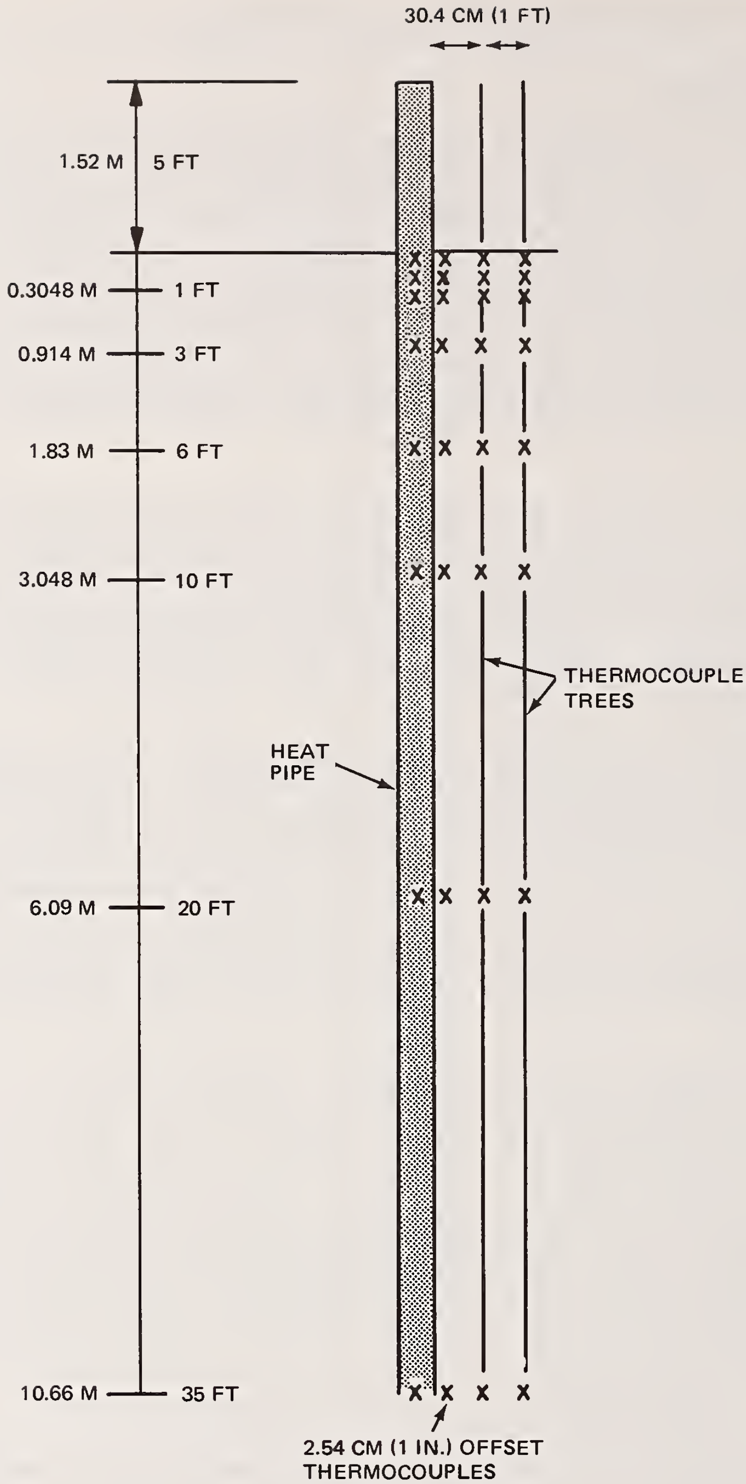


Figure 24 Earth heat pipe thermocouple locations

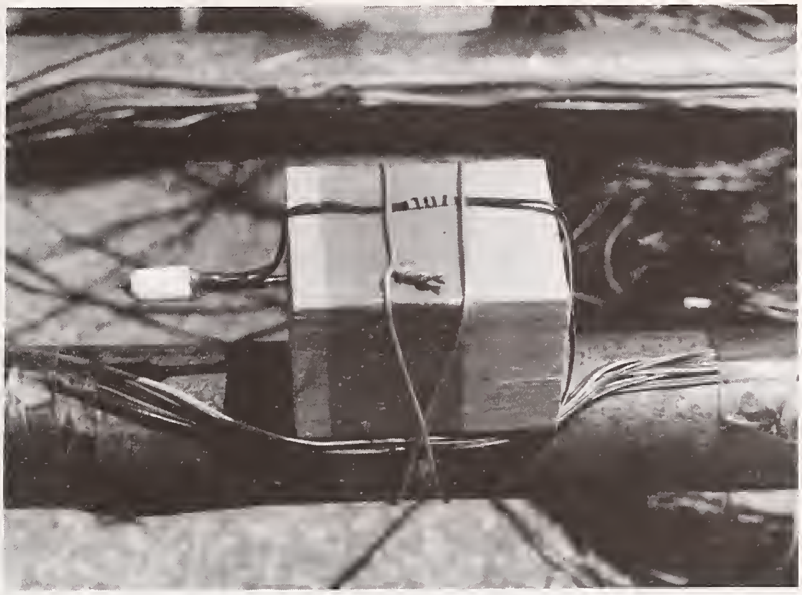


Figure 25 Earth heat pipe instrumentation — offset blocks

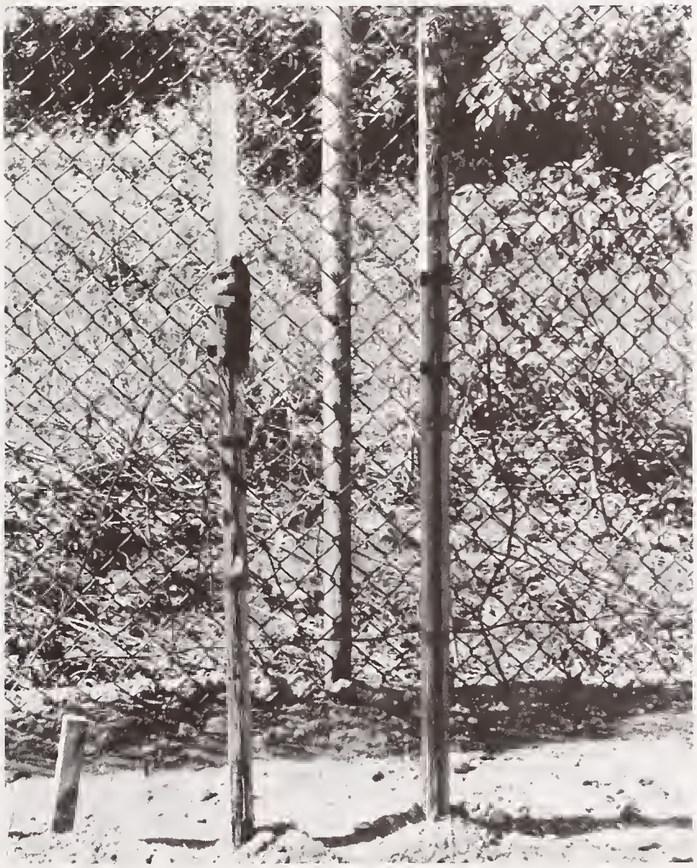


Figure 26 Instrumentation trees installed in ground

Figure 28 Installation of metal casing

Figure 29 Raising of earth heat pipe by crane

Figure 30 Earth heat pipe ready for insertion into metal casing in ground

Figure 31 Earth heat pipe being guided into casing

Figure 32 Earth heat pipe in casing

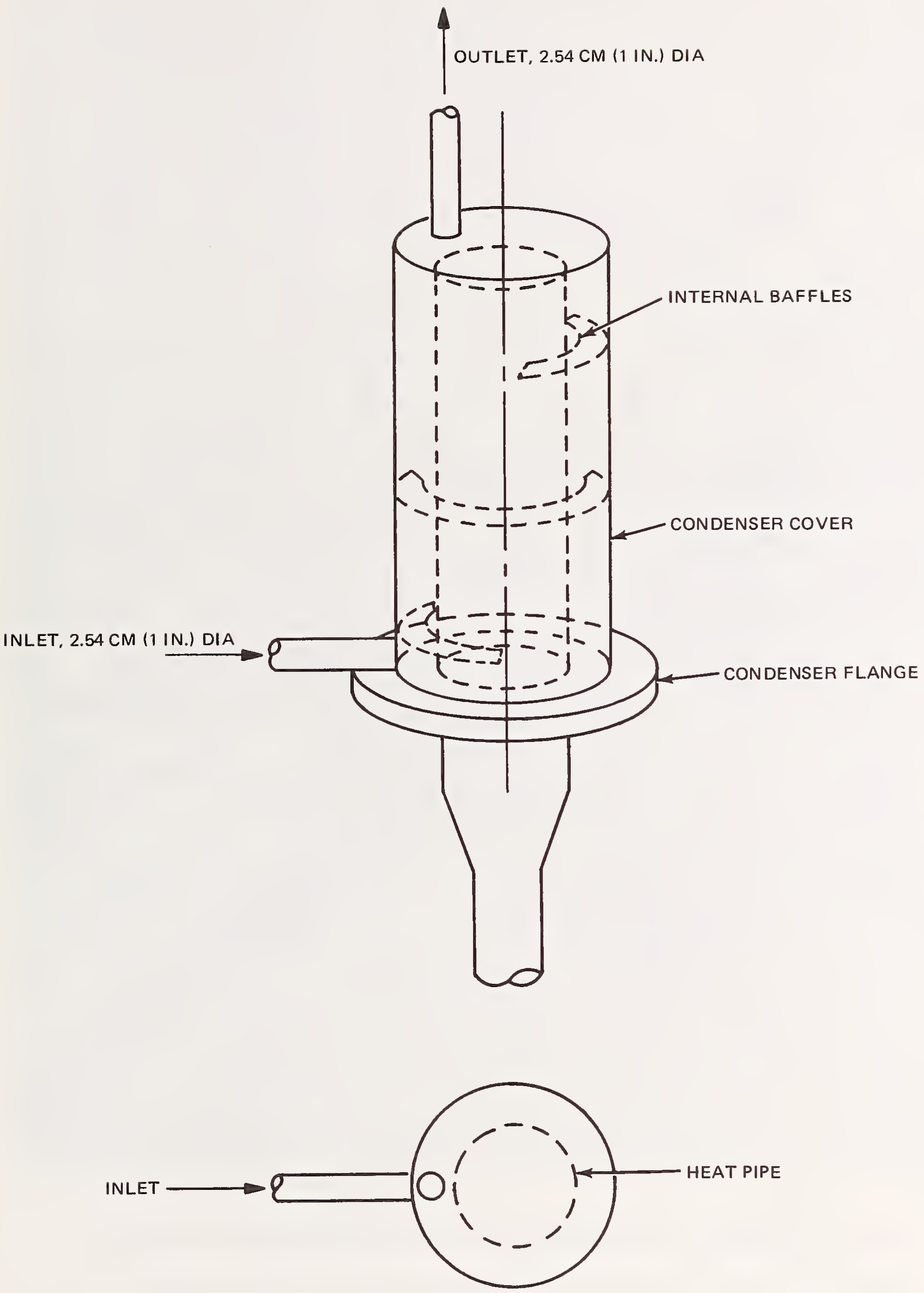


Figure 33 Condenser cooling configuration

Figure 34 Condenser end of 1- and 2-inch, nominal, earth heat pipes before installation

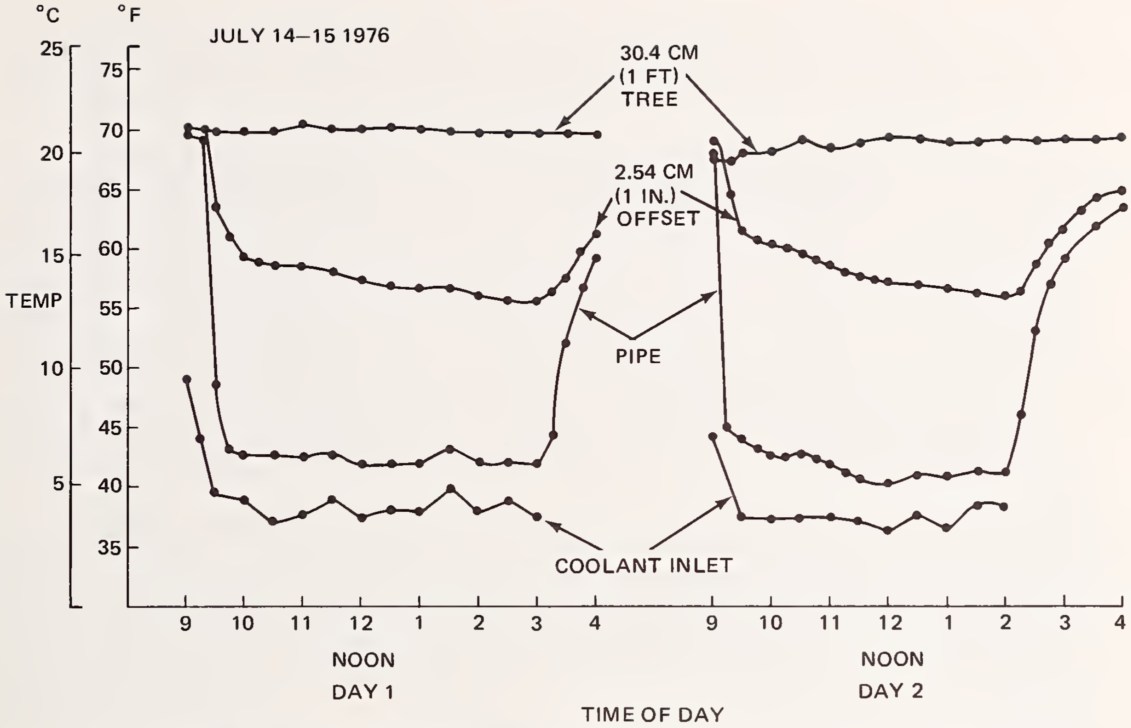


Figure 35 Earth heat pipe test results — 5 cm (2 inch) pipe, 30.48 cm (1 ft) depth

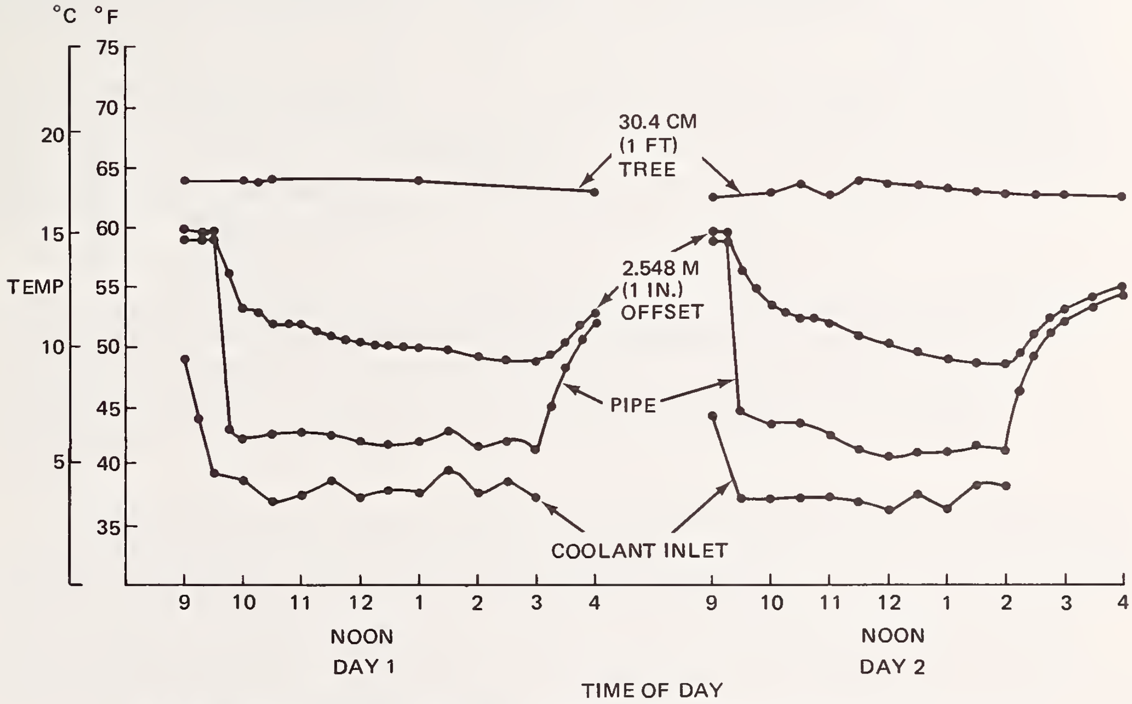


Figure 36 Earth heat pipe test results — 5 cm (2 inch) pipe, 3.048 m (10 ft) depth

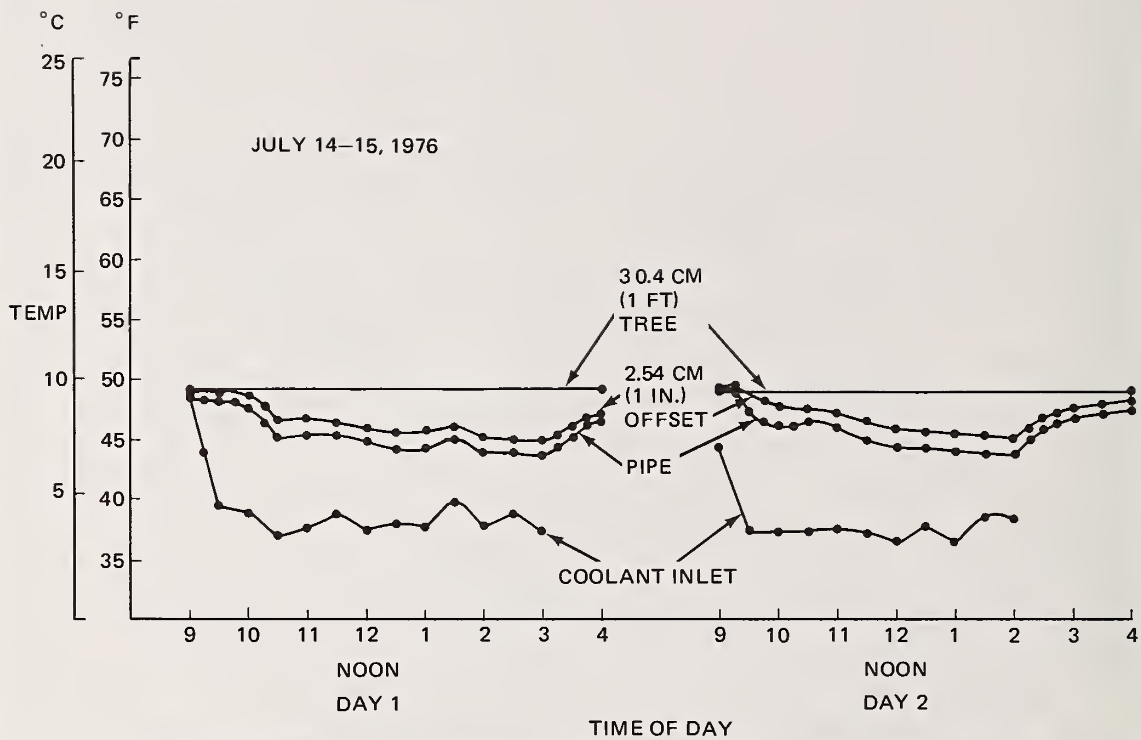


Figure 37 Earth heat pipe test results — 5 cm (2 inch) pipe, 10.66 m (35 ft) depth

the Reference 2 analysis.) This constant temperature indicates that, as expected, heat was removed from less than a 30.48 cm (1 ft) radius of soil over the two-day, simulated icing event.

The heat pipe and 2.54 cm (1 inch) offset thermocouple temperature readings dropped suddenly after the cooling water was applied, but then declined slowly over the rest of the test. At the 3.048 m (10 ft) depth, for example, the heat pipe temperature decrease was less than 0.5°C (1°F) over the last 5 hours of the first day of testing, figure 35; this indicates that even with continuous operation, pipe temperature will not degrade significantly over this period, once operating temperatures have been established. Note, also, the speed with which both the heat pipe and soil temperatures recovered after the flow of cooling water was stopped. This recovery demonstrates that the system recovers quickly, even after a severe six hour event. These experimental results compare favorably with the analytical results shown in figure 7.

Table 12 presents an hourly summary of the heat flux rates observed in the experiments. The variations in the temperature of the water flow are due to the operating characteristics of the Dunham-Bush package chiller used for the test; that chiller cools the water until it reaches a set minimum temperature and then shuts off until the circulating water temperature increases by about 2.28°C (5°F). Some improvement was effected by manually overriding the chiller controls.

The total amount of heat removed from the pipe was calculated at 3.44 kwh (11,762 Btu) for the first day and 2.441 kwh (8335 Btu) for the second day, or an average of 0.57 kw (1950 Btu/hr) and 0.488 kw (1667 Btu/hr), respectively. The decline from the first day to the second is probably due to the decline in the average soil temperature around the pipe.

The rates of energy flow at the bottom of the pipe at the end of the tests (6 hr) were determined from the offset thermocouple-to-pipe ΔT and based on soil thermal conductivities of 1.29 and 1.729 w/m-°C (0.75 and 1 BTU/hr-ft-°F). These rates were 6.53 and 8.65 w/m (6.8 and 9 Btu/hr-°F), respectively. The flow rates at the upper part of the pipe were unrealistically large due to the summar temperature profile of the earth.

In order to compare computer model and the test results, a computer run was made using the experimentally measured earth temperature profile for the first day with the heat pipe temperature initially set to the test level. As shown in figure 38, the agreement between test and model is good; the differences that were obtained are probably due to differences between experimental and programmed values of soil capacitance, conductivity, and density.

Results for a one-day test of the 2.54 cm (1 inch) heat pipe are presented in figures 39, 40, 41. These results resemble those for the 5 cm (2 inch) pipe, except for the slow reaction of the lower part of the pipe. This slower reaction may be due to the lower capacity of the 2.54 cm (1 inch) pipe, or to unmeasured variations in water flow temperature. The heat flux removed from the 2.54 cm (1 inch) pipe is summarized in table 13. As expected, the values are lower than for the 5 cm (2 inch) case.

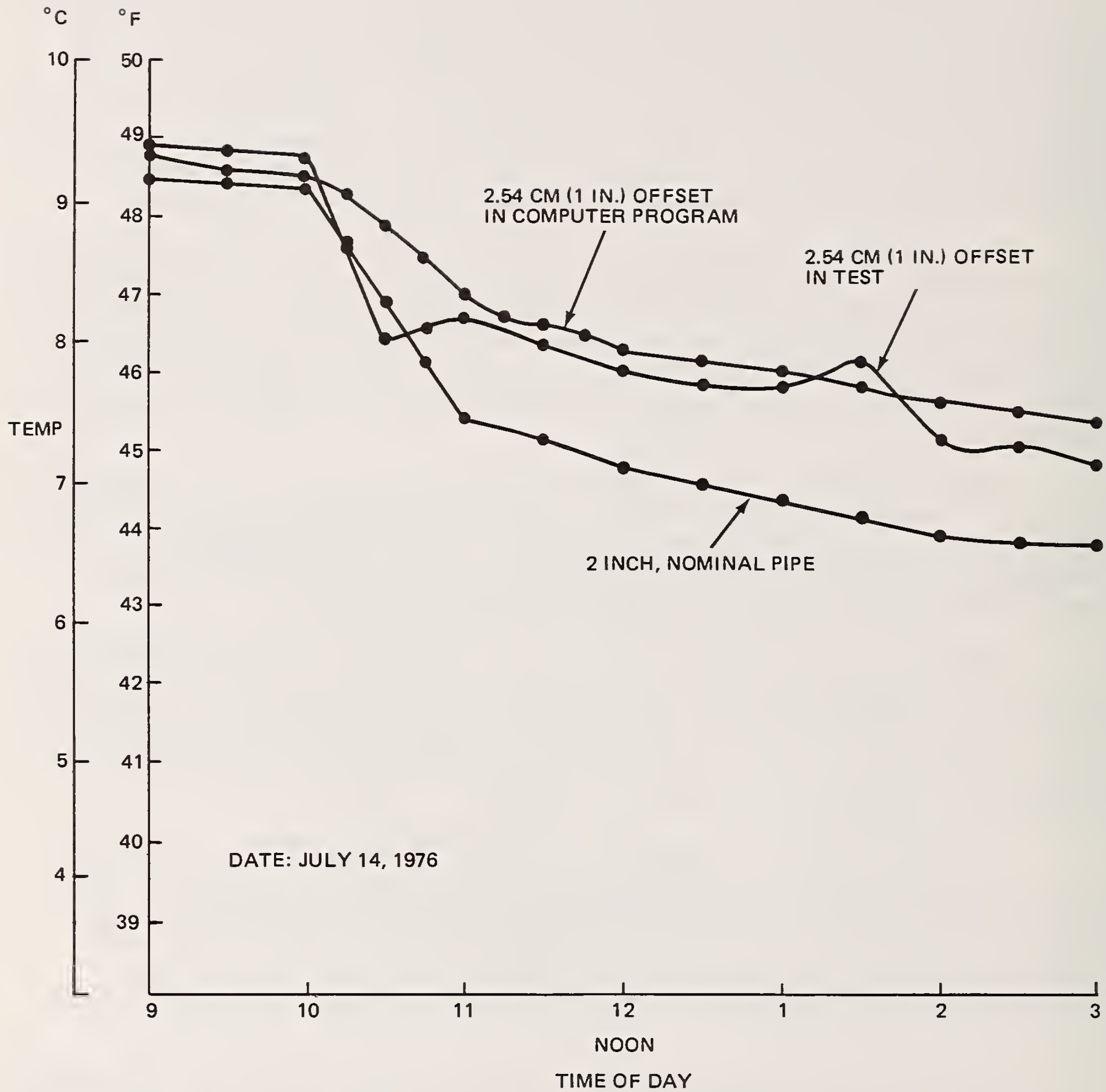


Figure 38 Comparison of test results and computer model of 2.54 cm (1 inch) offset temperatures at 10.66 m (35 ft) depth

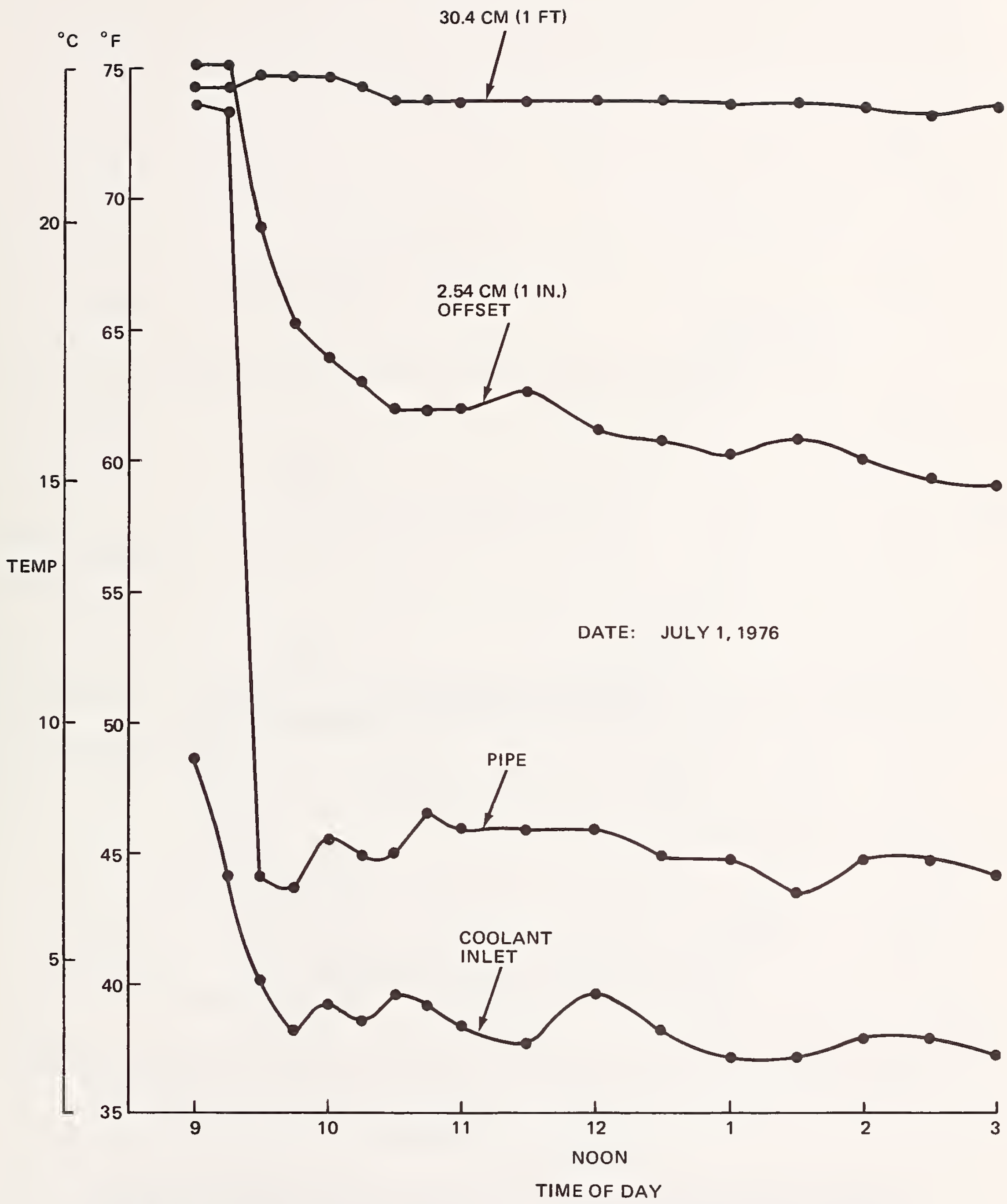


Figure 39 Earth heat pipe test results — 1 inch, nominal, pipe, 30.48 cm (1 ft) depth

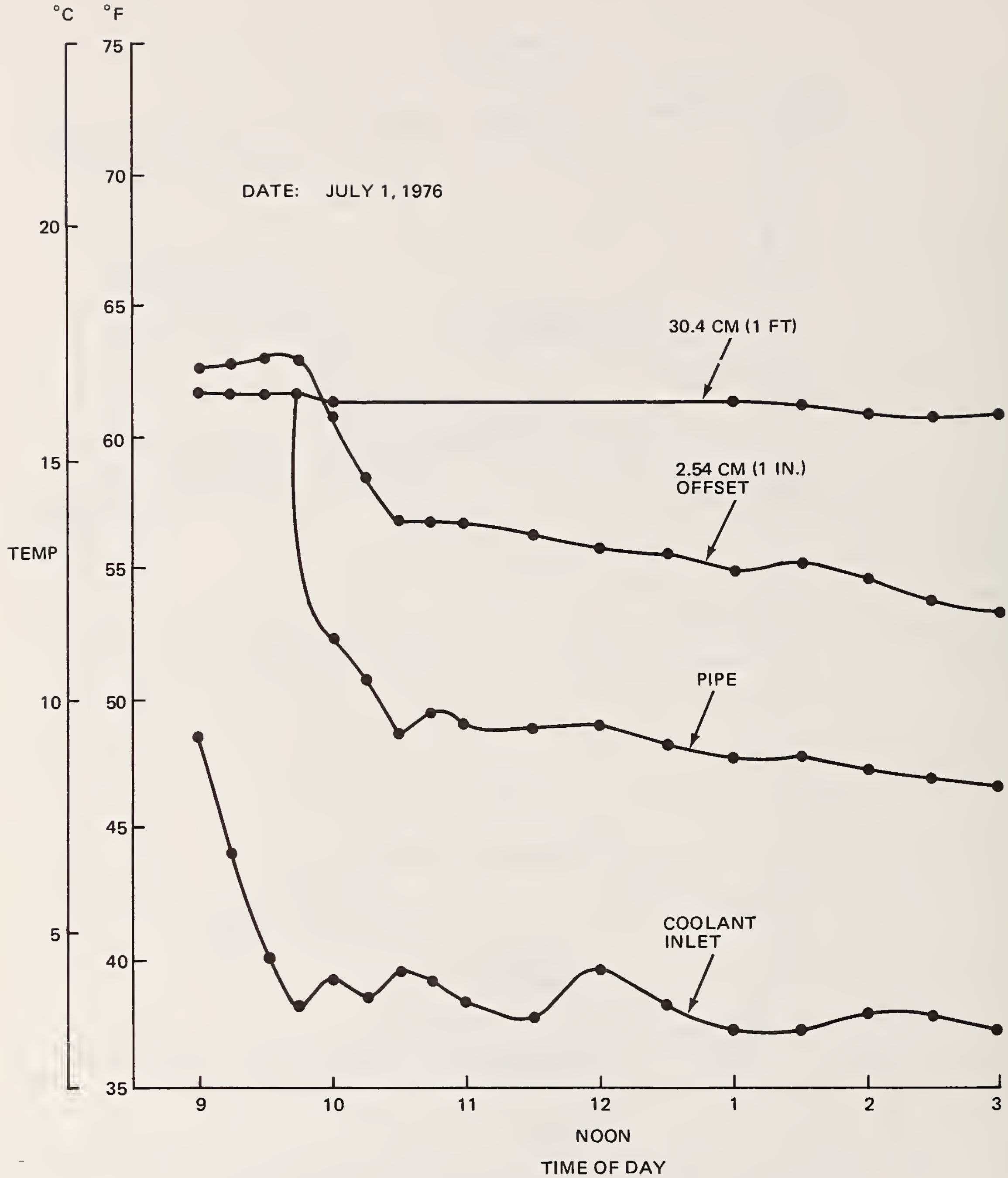


Figure 40 Earth heat pipe test results — 1 inch, nominal, pipe, 3.048 m (10 ft) depth

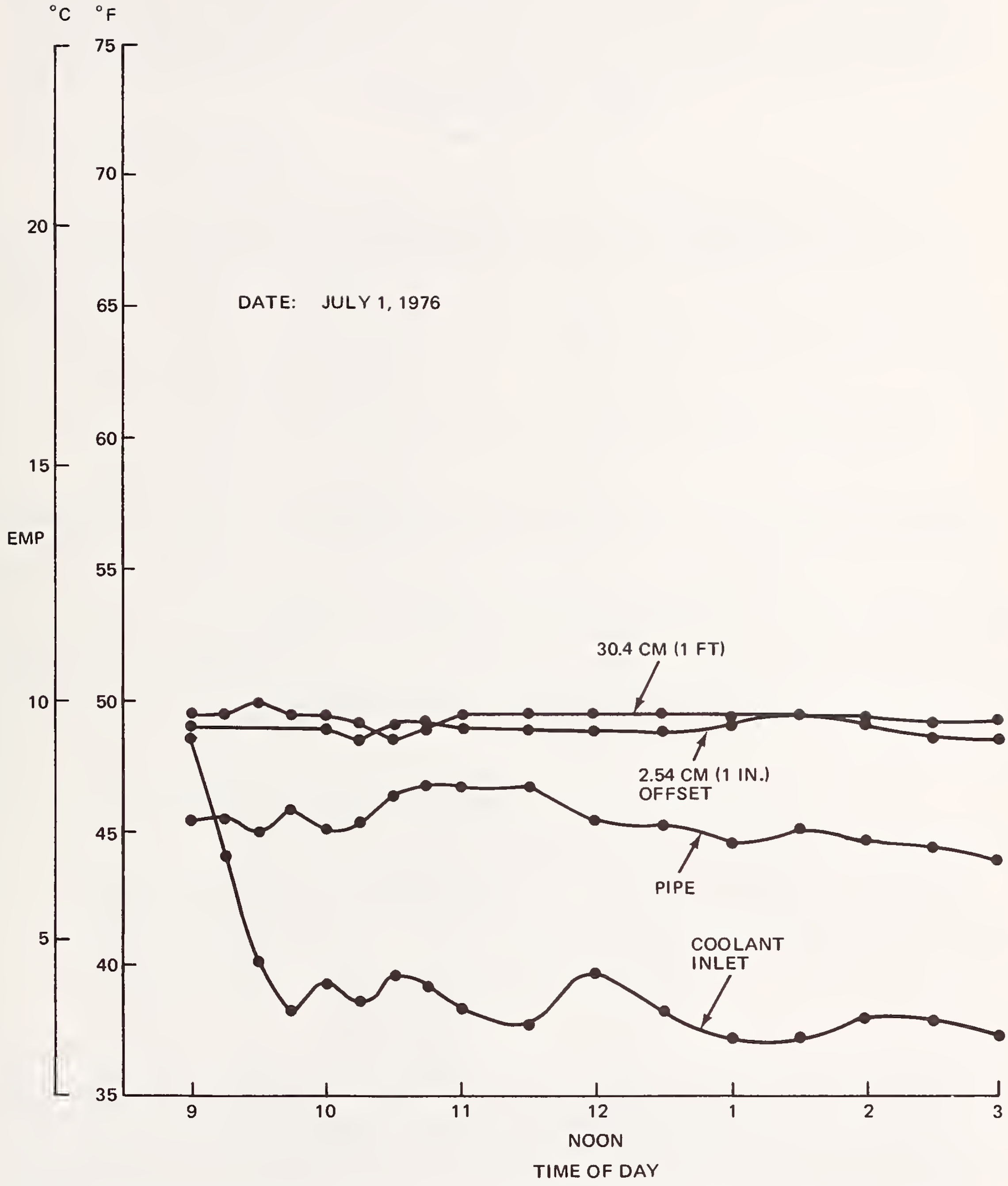


Figure 41 Earth heat pipe test results — 1 inch, nominal, pipe, 10.66 m (35 ft) depth

Table 12 Energy Removed from 5 Cm (2 Inch) Heat Pipe

Day	Hour	* Energy Removed	
		Kwh	Btu
1	9-10	0.721	2463
	10-11	0.771	2632
	11-12	0.494	1687
	12-1	0.512	1748
	1-2	0.554	1890
	2-3	0.375	1282
2	9-10	0.632	2160
	10-11	0.425	1451
	11-12	0.415	1417
	12-1	0.514	1755
	1-2	0.454	1552

Day 1
Total Energy Removed = 3.428 Kwh (11,702 Btu)
Average Energy Removed = 0.57 Kw (1950 Btu/Hr)

Day 2
Total Energy Removed = 2.44 Kwh (8335 Btu)
Average Energy Removed = 0.488 Kw (1667 Btu/Hr)

Table 13 Energy Removed From 1 Inch, Nominal, Heat Pipe

Hour	Energy Removed	
	Kwh	Btu
9-10	0.297	1012
10-11	0.297	1012
11-12	0.593	2025
12-1	0.435	1485
1-2	0.593	2025
2-3	0.652	2227

Total Energy Removed = 2.867 Kwh (9787 Btu)
Average Energy Removed = 0.478 Kw (1630 Btu/Hr)

In order to determine the value of soil thermal conductivity, samples of the soil at 10.67 m (35 ft) were taken and tested; an average value of about 1.29 w/m- C (0.75 Btu/hr-ft) was obtained. However, since the soil samples crumbled easily, they might not have been representative of real soil. Moreover, the process of back filling the hole after the pipe was inserted may have resulted in a denser packing of the soil than normally exists in undisturbed earth.

2.6.2 Valved Heat Pipe

The valved heat pipe test was performed to evaluate the performance of a low-cost, commercially available electrically actuated valve for use as a heat pipe shutoff device in the bridge de-icing system. The following specific items were to be determined:

- The amount of heat leakage between the evaporator and condenser when the valve is closed
- The amount that the valve impedes heat pipe action at design heat loads (if at all)

A secondary item to be determined was the speed with which the pipe responds when the valve is opened under load conditions.

In order to be used for heat pipe bridge de-icing applications, a valve must be capable of satisfying the following requirements:

- Must be ammonia compatible (no copper or brass)
- Must not inhibit the flow of liquid or vapor (flow passage through the valve must be large)
- Must be capable of operating (opening) when a considerable pressure differential exists across the valve; as a design guideline, based on an air temperature of -17.8 °C (0°F) and a pipe temperature of 10°C (50°F), the pressure across the valve would be 4.12 kg/cm^2 (58.64 psi) for ammonia, or $P_{10°C}$ = 6.254 kg/cm^2, $P_{-17.8°C}$ = 2.131 kg/cm^2 ($P_{50°F}$ = 88.96 psi, $P_{0°F}$ = 30.32 psi).

Several types of valves can be considered for this application: solenoid, ball, and gate valves. Basically, there are three types of solenoid valves: pilot piston pressure operated types, semi-direct lift types, and direct lift types. The first two types depend upon the flow of liquid to open and close the valve. This operation is unsuitable for this case since a steady unidirectional single phase flow is not available; the direct lift type is suitable for this application since it uses only electric power.

A typical, direct lift valve, as shown in figure 42, opens and closes at right angles to the flow path, with the flow path blocked at the half depth level (section A). As this blockage prevents the back flow of a puddle and requires an excessive depth of fluid, this valve cannot be used for horizontal pipe application. Moreover, large ports are hard to find in available direct lift valves; a maximum size of 2.54 cm (1 inch) is common since the solenoid in a direct lift valve must act against the entire pressure difference between the two sides of the pipe. With a temperature differential of 20°C (50°F) across the valve, the solenoid would have to act against a total force of ~83.6 kg (84 lb) for a 5 cm (2 inch) port:

$$\pi R^2 p = (2.5)^2 \times \pi \times 4.122 = 83.6 \text{ kg} = (1)^2 \times \pi \times 58.64 = 184.2 \text{ lbf}$$

A solenoid such as this would have to be quite large; and no commercially available valve which could meet this requirement was identified. Moreover, since the larger solenoid valves which approach this value use outside lever systems, a completely enclosed casing about the valve cannot be used (one of the desirable characteristics of solenoid valves). Therefore, solenoid valves were judged unacceptable for this application.

Butterfly, or gate, valves, figure 43, meet each of the listed design requirements. With this design, flow passage is straight and valves with 5 cm (2 inch) or greater diameters can be purchased. Stainless steel valves which can handle ammonia and electric actuator attachments are also commercially available. Typically, a 5 cm (2 inch) diameter stainless steel butterfly valve with solenoid attachment will cost about $350. This price is in fact less than that for similarly sized ordinary solenoid valves, which range from $400 to $700.

Ball valves, figure 44, also meet the design requirements. As with the gate valve, the flow passage is straight, and in this case totally unobstructed.

Based on the evaluations, 5 cm (2 inch) diameter gate and ball valves were ordered for the test program. Valve materials were steel and plastic to assure compatibility with ammonia.

The valve test specimen, figures 45 and 46, consisted of 1.83 m (6 ft) long, 2 inch, nominal, carbon steel pipes, with the valves installed in the middle. The ball (Jamesburg) valve was welded into place; the gate (Garlock) valve was bolted into place between flanges.

After construction of the valve test specimens, they were subjected to a pressure integrity test to check for gross leaks. The entire specimen was immersed in water and pressurized with nitrogen to 30.2 kg/cm (430 psia) to provide 1.5 times the maximum internal ammonia pressure that would exist at the expected maximum pipe temperature of 48.9°C (120°F). After the specimen was pressurized the valve was opened and closed to check the quality of the valve stem seal. Finally, with the valve closed, one side of the specimen was depressurized to check the valve behavior under unequal loading. No leaks were found in either specimen during any of these tests.

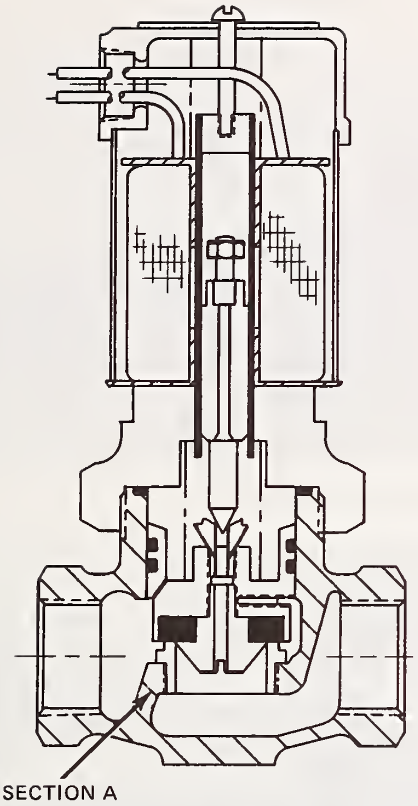


Figure 42 Solenoid valve

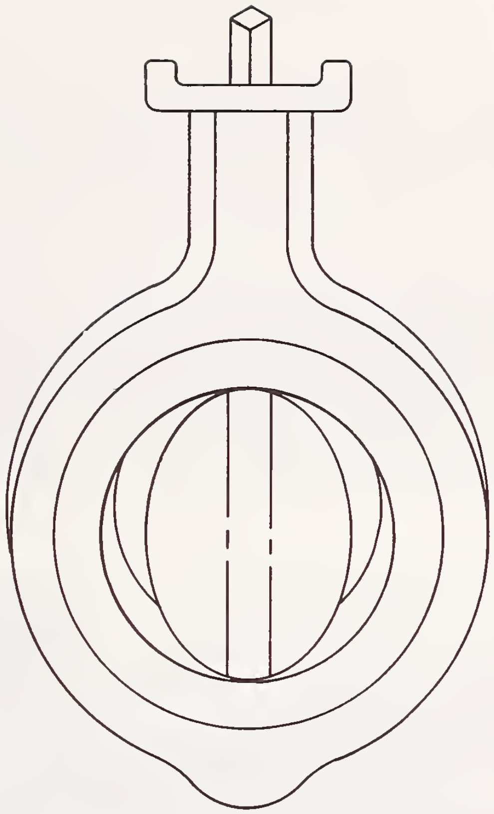


Figure 43 Butterfly valve

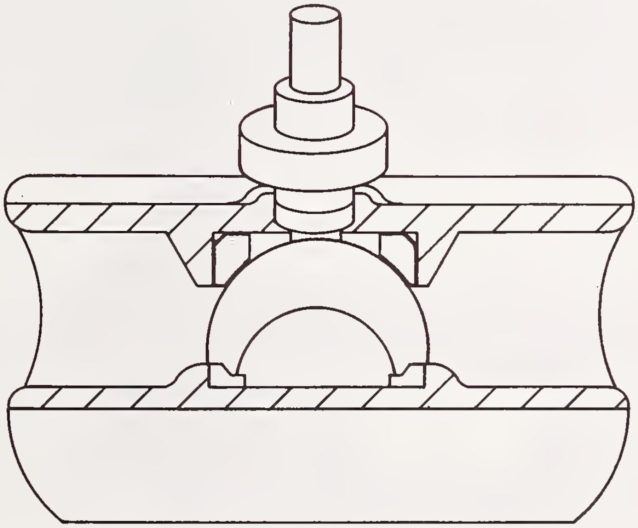


Figure 44 Ball valve

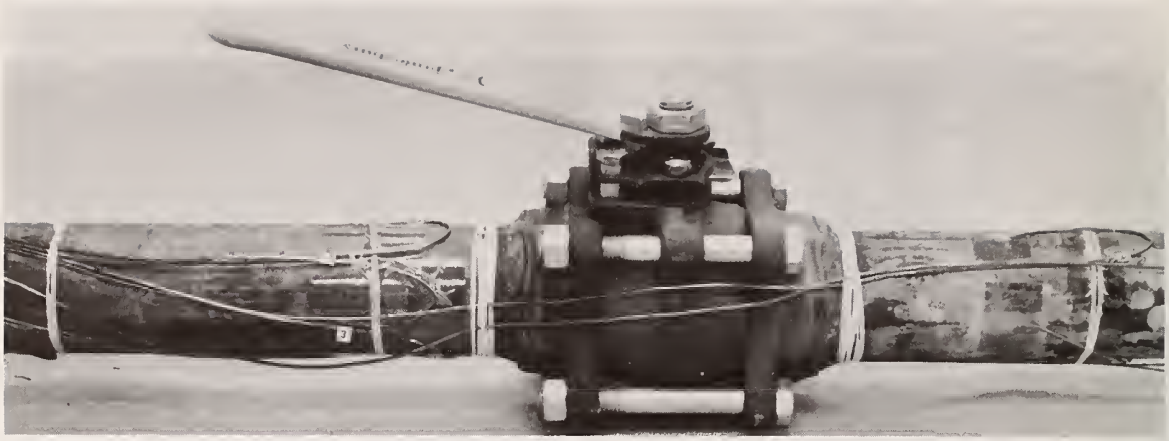


Figure 45 Ball valve installed between pipe sections

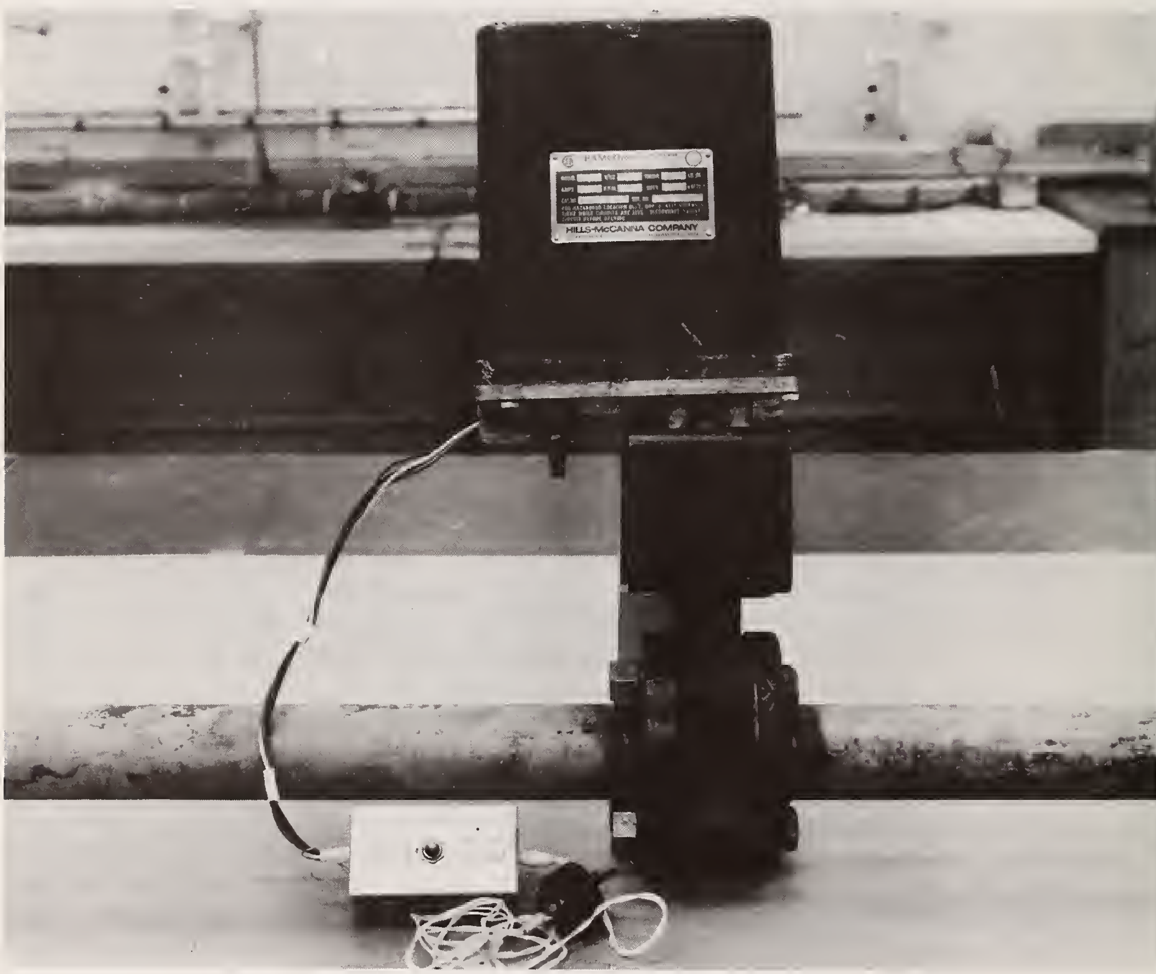


Figure 46 Butterfly valve (with electric actuator) installed between pipe sections

Because of its more rugged design, the Jamesburg ball valve was selected for the remainder of the tests. The specimen was charged with 337 gm of ammonia by vapor transfer. After reaching room temperature of 21.2° C at 8.99 atmospheres (70°F at 128 psi), the valve was tested for ammonia leakage by use of red litmus paper; no leakage was detected. A more sensitive test employing copper sufate/ethylene glycol detection techniques also was employed, with no leak detected at a sensitivity of 10^{-7} std cm^3 per second. The specimen was instrumented and set up for the performance test as shown in figure 47. The condenser was cooled by a water spray bath of ~13°C (56°F) and heat was supplied to the bottom of the evaporator by an electrical resistance (strip) heater to simulate actual performance. The entire setup, except for the condenser section, was insulated.

In order to determine the heat leakage across a closed valve, sufficient power was provided to maintain the evaporator at 21.1° C (70° F); this resulted in an evaporator-condenser temperature drop of about 7.7°C (14°F) and a heat leakage of 8 watts; in a corresponding real situation the evaporator would be at about 8.4 to 10° C (48 to 50° F), and the condenser at about 0 to 1.7° C (32 to 35° F). In order to study transient response, the test valve was opened at these conditions. As shown in figure 48, the evaporator cooled to the condenser temperature in about 3 to 4 minutes; though this represents the time needed to cool the mass of the pipe, the pipe was probably active for a much shorter time. Unfortunately, pipe length, another important variable in pipe response time, was not adequately considered in this test.

After transient response testing, power was incrementally increased to a load of 2400 watts, the point at which the heater ribbon was about to burn out. The temperature distribution is shown in figure 47. As indicated in the figure, although the condenser-to-evaporator temperature has increased greatly, variation between the evaporator (thermocouples 3, 4, 5) and condenser (thermocouples 6, 7, 8) temperature is not significant. The relatively high and low temperatures recorded for thermocouples 1, 2 and 9, 10 are caused by the proximity to the electrical heater and water spray bath, respectively. Thermocouple 11 indicates water exhaust temperature.

The generally satisfactory results of these tests indicate that valved heat pipes can be built to satisfy the system design requirements.

2.6.3 Heat Pipe/Heat Pipe Joint

The heat pipe interface joint conductance is a function of the internal heat pipe film coefficient, heat pipe wall thickness, and the type and quality of the pipe-to-pipe interface. Joint conductance, figure 49, is defined as follows:

$$Hj = Qj/Aj\ \Delta Tj$$

where:

$Q_{evap} = Q_{cond} = Qj$ = Heat carried through pipes and across joints, cal/hr

$hj\left(\frac{1}{Rj}\right)$ = overall joint conductance, cal/cm^2-°C

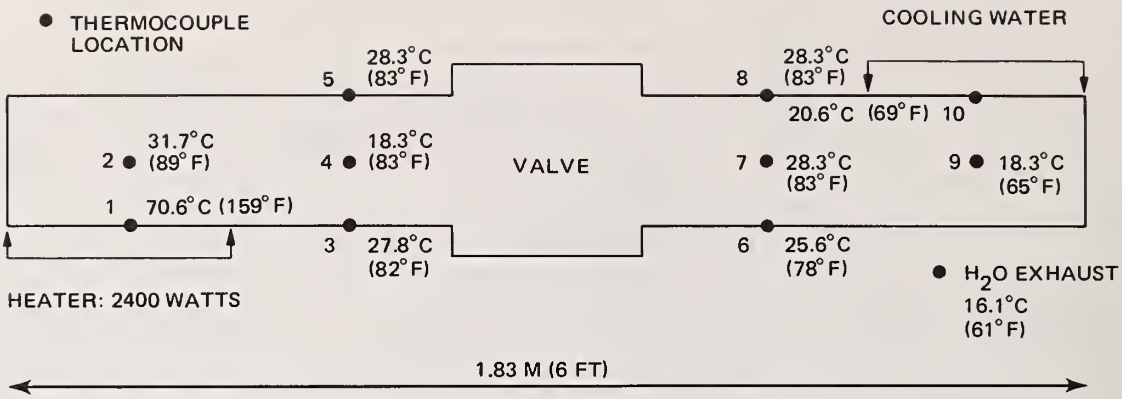


Figure 47 Temperature map for valved heat pipe transporting 2400 watts

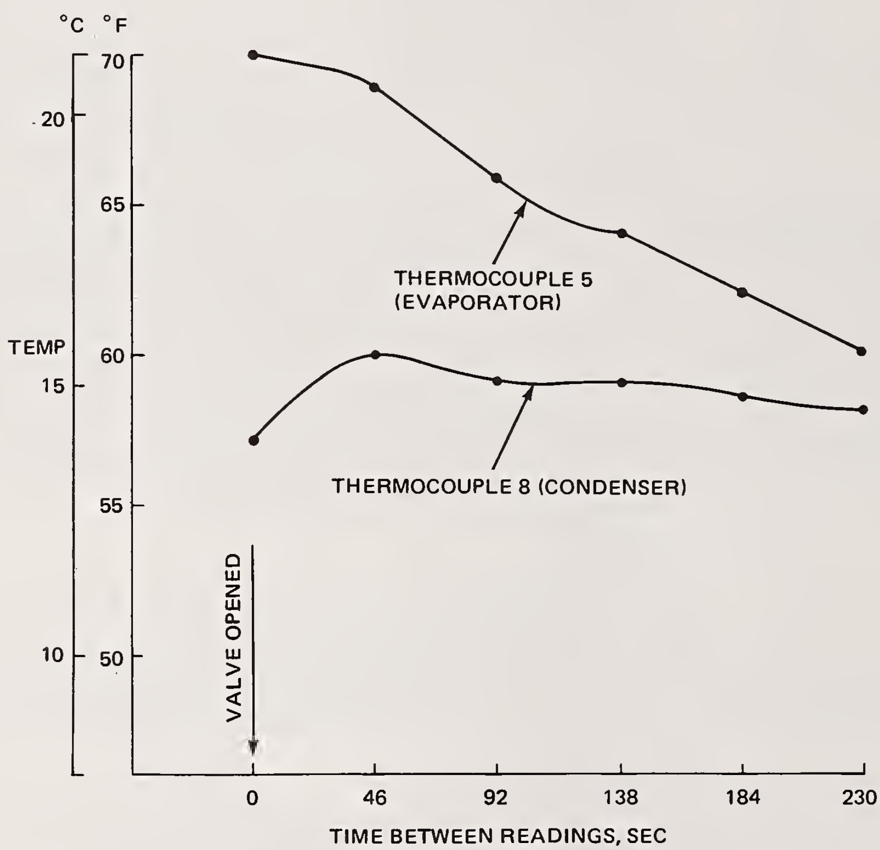


Figure 48 Valved heat pipe test – temperature stabilization after valve opening

$R_j\left(\frac{1}{h_j}\right)$ = overall joint resistance, hr-cm^2-°C/cal

A_j = joint contact area, cm^2

ΔT_j = vapor temperature difference of joined heat pipes, °C

Note that joint temperature drop has been minimized by positioning the condenser section of heat pipe 1 below the evaporator section of heat pipe 2. Since evaporation occurs predominantly at the contact miniscus between the liquid and wall, this orientation provides the shortest wall length (resistance) from the condensing surface to evaporator line. The process may be depicted as shown in figure 50, with arrows in the figure used to represent the flow of heat.

The heat pipe/heat pipe joint test program was performed to determine joint conductance per unit length of joint, and thus enable the calculation of joint length required to provide an acceptance temperature drop (Δ Tj) for a given rate of heat transfer (Qj). Since selection of a joint for this program is based on tradeoffs between thermal efficiency, expense, and ease of field assembly, FHWA requested that joint conductance be measured on at-least five designs, both before and after imposing the joints to typical vibration loading.

Since the described bridge de-icing system uses earth heat pipes, which are connected to the bridge heat pipes via headers, at least two joints are required in the system: one between the earth heat pipes and headers and the other between the headers and the bridge heat pipes. Moreover, handling considerations may require the use of more than one header length between the earth and bridge, with even more joints thus required. A poor joint conductance thus has significant impact on system design.

In order to develop the required design information, hardware simulating earth, header, and bridge heat pipes was built and tested. All of the test heat pipes were of the same inner and outer diameters and material as the proposed design, and the joints were assemblied as they would be by field personnel.

Figure 51 represents the typical test setup used to perform the joint tests. The arrangement shown in the figure enabled the simultaneous evaluation of joint conductance across the earth-header and header-bridge heat pipes. Since coupling different diameter pipes requires different hardware, and will yield different conductances, each setup provided for the simultaneous testing of two joint types for each design; i.e., coupling a 2 inch, nominal, heat pipe to a 2 inch, nominal heat pipe and coupling a 2 inch, nominal, heat pipe to a 0.5 inch, nominal heat pipe.

Each of the heat pipes was fabricated of carbon steel material (per ASTM A-120), and was charged with anhydrous ammonia with a minimum certified purity of 99.99 percent. Instrumentation was attached so that overall conductance across the joint could be calculated for a given power level and joint area. A heater was attached to the evaporator section as shown in figure 52, the setup was insulated, and testing was performed at about room temperature to minimize environmental heat losses.

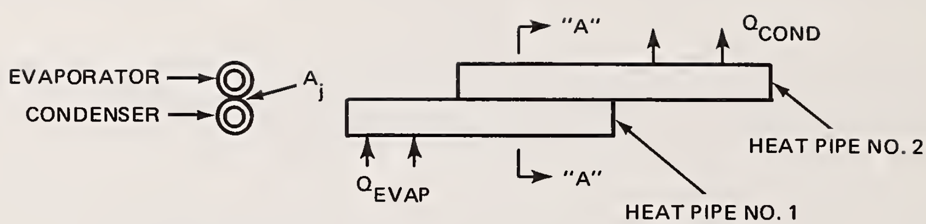


Figure 49 Joint conductance definitions

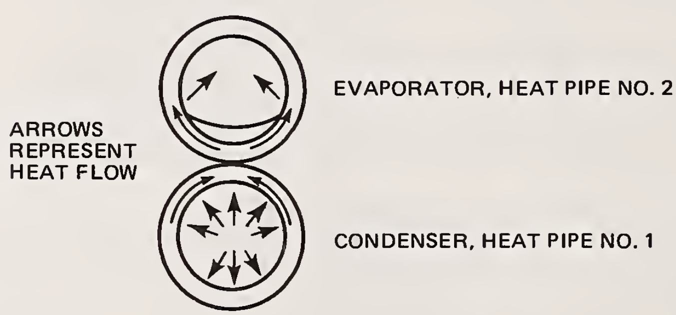


Figure 50 Evaporation at contact meniscus between liquid and wall

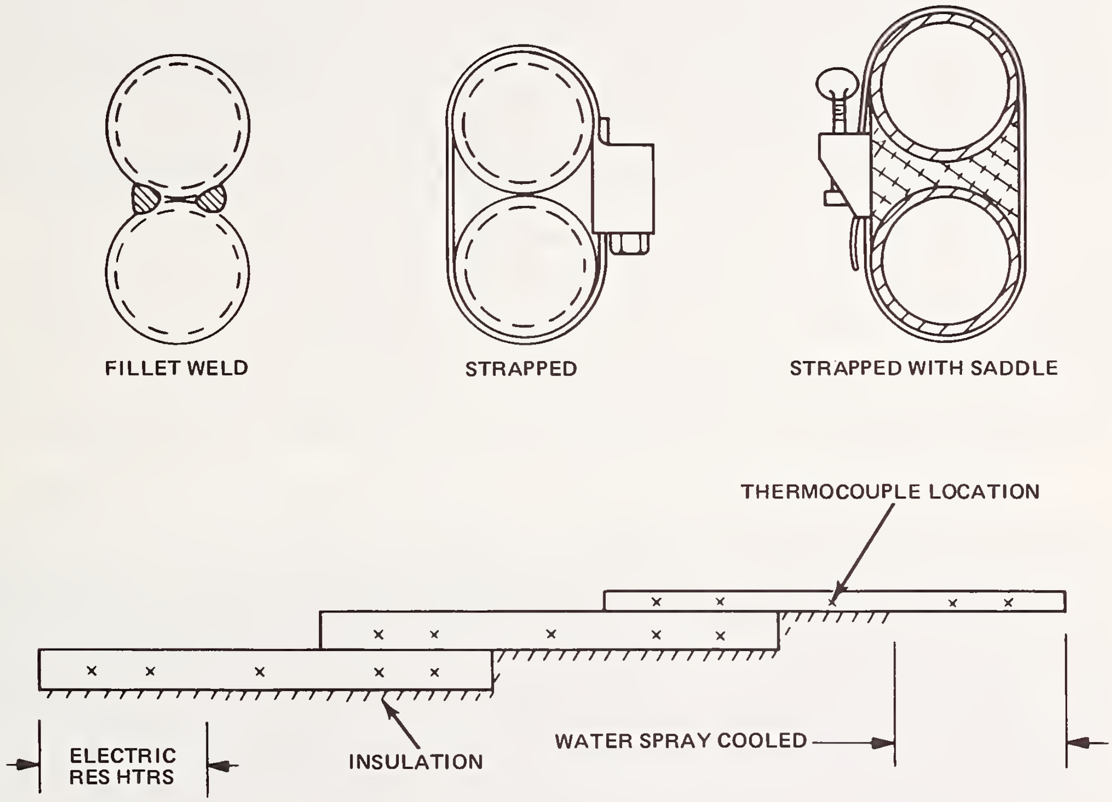


Figure 51 Heat pipe joint test setup

On the basis of existing test data for aluminum tube joints, Reference 5, the following basic joint designs were selected for test:

- strapped
- strapped/saddle
- welded.

Of these basic designs, the simple tension strapped joint would obviously be the simplest configuration for construction workers to assemble, figure 53. Although flattening the tubes and applying an interfacial grease or conductive filler would improve strapped joint performance, the increased cost, decreased reliability, and added assembly complexity would be undesirable; if flattened surfaces were not properly aligned by field personnel, such that good flat-to-flat contact was made, the joint conductance would degrade significantly from that obtained in laboratory tests.

Placing a saddle between the heat pipes improves the contact area, and may increase the joint conductance. Therefore, the strapped/saddle joint, shown in figures 54 and 55, was also tested. Since the basic material used, low-carbon steel, has the relatively low thermal conductivity K~4.3 w/m-°C (25 Btu/hr-ft-°F), the saddle must be as thin as practical. In addition, the joint should be fairly simple to assemble by construction crews. Obviously, such a joint is more expensive than a simple strapped joint due to the manufacturing cost of the saddle. Thermal grease (Dow Corning 340 Silicone heat sink compound) should be applied in the joint to improve performance.

The third joint tested, the welded specimen, is joined by a weld along the line of contact, figures 56 and 57.

The three specimens actually tested are shown in figures 58 through 60. Ordinary pipe clamps were used in the simple strapped design, figure 58, tightened as much as possible with a large screw driver. Since poor thermal conductance was expected, a 5 cm (2 inch) pipe was attached. Table 14 summarizes the test results achieved. As shown in the table a very low maximum value of conductivity for this joint of 13.78 w/m-°C (7.97 Btu/hr-ft-°F) was obtained, as measured from the surface of the evaporator (away from the heater) to the surface of the condenser (away from the cooling water). With a 2.78°C (5°F) temperature drop across the joint, and a typical heat flow rate of 0.45 kw (3250 Btu/hr) the joint would have to be 25 m (82 ft) long. Based on these results, testing proceeded directly to the strapped/saddle-grease and welded designs.

Results for the strapped/saddle-grease and welded designs are also given in table 14. As shown in the table, the joint conductance between the 2 inch, nominal, pipes is somewhat better than the joint conductance between the 2 inch, nominal, and the 1/2 inch, nominal, pipe. The slight increase in conductivity with increased heat flow is probably due to improved internal fluid film coefficients. Although the welded design provides better performance than the strapped/saddle design, neither design provides

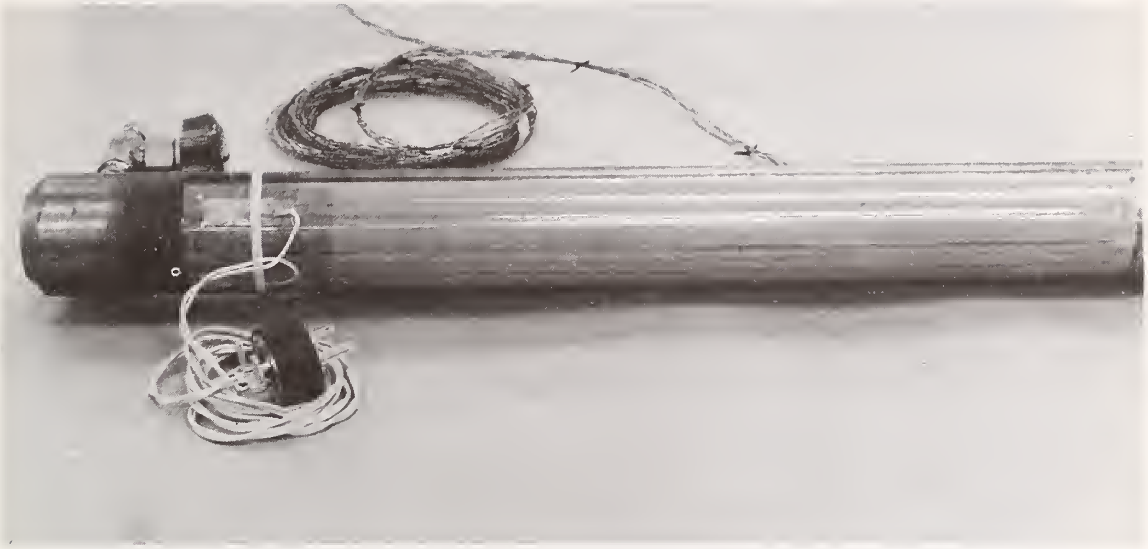


Figure 52 Electric heater installed on pipe

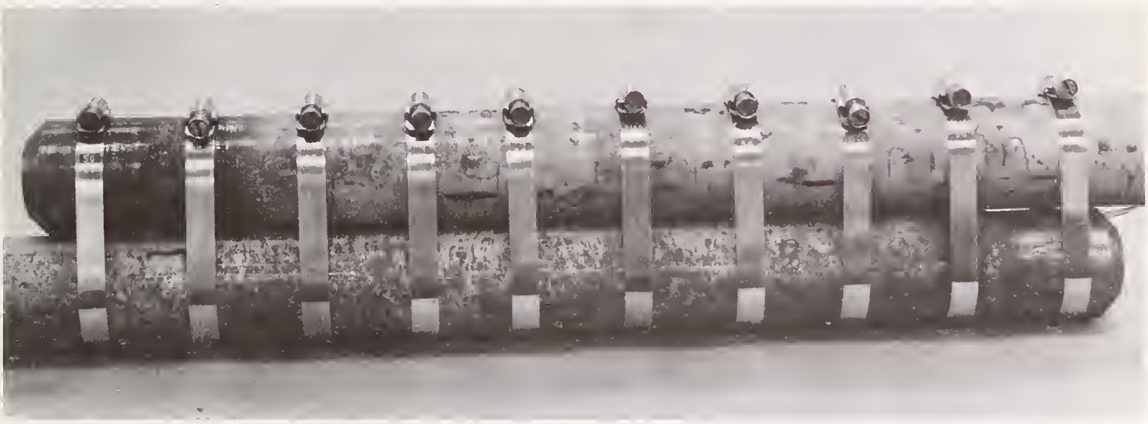


Figure 53 Simple strapped joint — 2-inch-pipe to 2-inch-pipe

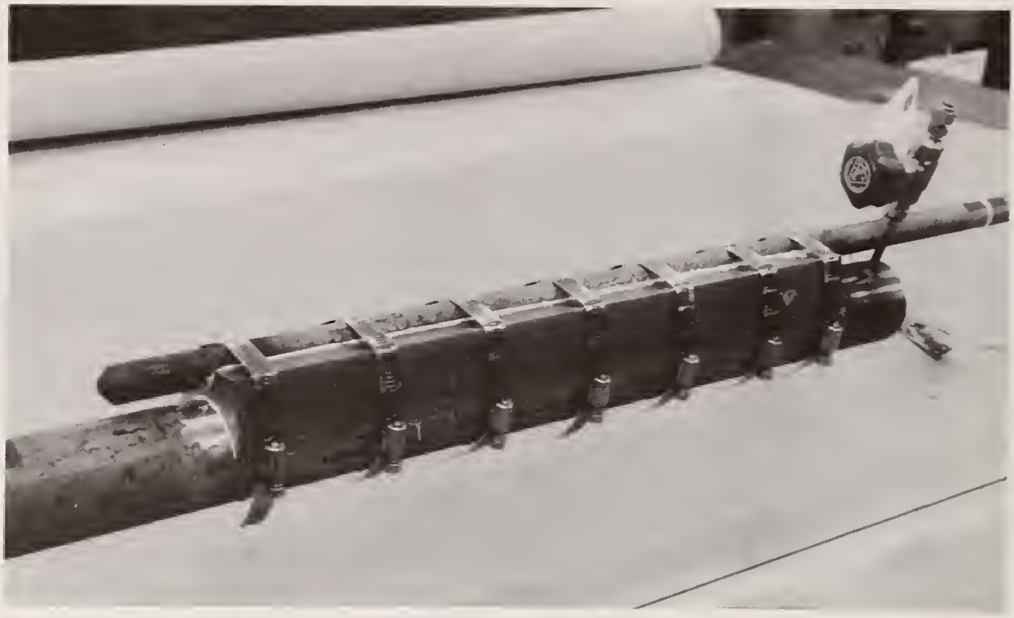


Figure 54 Strapped saddle joint — 2-inch-pipe to ½-inch-pipe

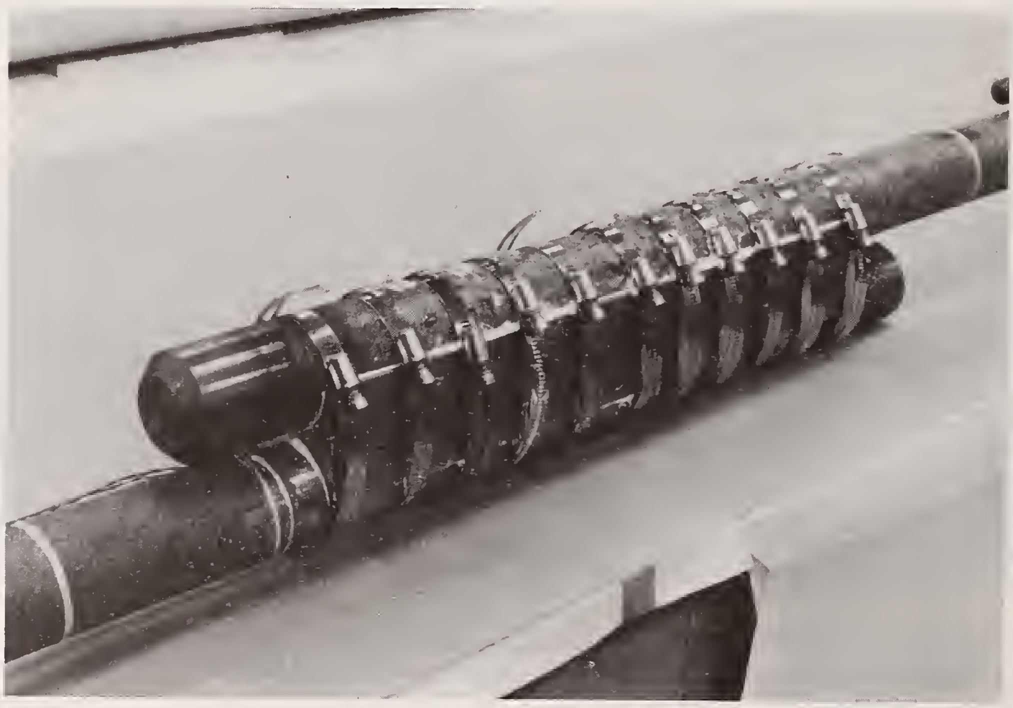


Figure 55 Strapped saddle joint — 2-inch-pipe to 2-inch-pipe

Figure 56 Welded joint — 2-inch-pipe to 2-inch-pipe

Figure 57 Welded joint — 2-inch-pipe to ½-inch-pipe

Figure 58 Simple strapped joint test specimen

Figure 59 Strapped saddle test specimen

Figure 60 Welded test specimen

Table 14 Heat Pipe/Heat Pipe Joint Conductive Test Results

Joint Type	Nominal Heat Pipe Sizes Joined, in.	Conductance			
		Before Vibration Test		After Vibration Test	
		w/m-°C at w	Btu/hr-ft-°F at Btu/hr	w/m-°C at w	Btu/hr-ft-°F at Btu/hr
Simple Strapped	2 to 2	13 at 115 13.4 at 154	7.6 at 394 7.8 at 525	14.1 at 115 13.6 at 154	8.2 at 394 7.9 at 525
Welded	2 to 2	43.6 at 100 55.3 at 211	25.2 at 340 32 at 720	35.8 at 100 40.5 at 211	20.7 at 340 23.4 at 720
	2 to 1/2	30.3 at 100 43.2 at 211	17.5 at 340 25 at 720	31.5 at 100 37.7 at 211	18.2 at 340 21.8 at 720
Strapped Saddle	2 to 2	29.7 at 100 36.1 at 211	17.2 at 340 20.9 at 720	32.6 at 100 36.8 at 211	18.9 at 340 21.3 at 720
	2 to 1/2	28.0 at 100 28.7 at 211	16.2 at 340 16.6 at 720	21.8 at 100 28.2 at 211	12.6 at 340 16.3 at 720

really satisfactory performance. The best result achieved, 55.3 w/m-°C (32 Btu/hr-ft-°F) for the welded joint, would require a joint length of 6.09 m (20 ft) for a load of 0.9 kw (3250 Btu/hr) and a joint ΔT of 2.78°C (5°F).

According to the FHWA request, the three heat pipe joint specimens were subjected to a low-frequency, narrow-band, random vibration test to determine their ability to withstand the environment after the first set of thermal tests were completed. Each specimen was tested, using the setup shown in figure 61, for one hour, at an overall input level of 27g, rms, over a 12.5 to 600 Hz frequency range. All joints withstood the test without structural failure or distortion.

After the vibration test was completed, the thermal tests were repeated. Results of those tests, also shown in table 14, confirm the fact that vibration does not significantly affect joint thermal conductance, and thus does not affect the conclusion that all of these joints require excessively long interfaces to meet system requirements.

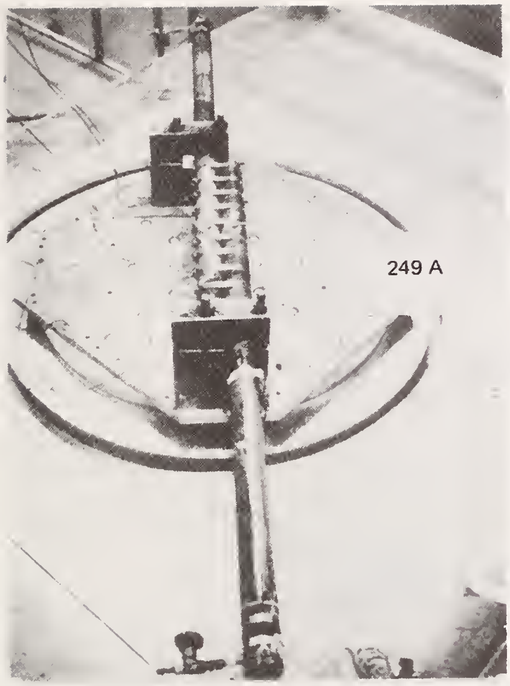
The poor thermal performance measured for each of these joint designs suggests that the use of a pumped fluid loop system, instead of a header heat pipe, should be investigated.

2.6.4 Slab

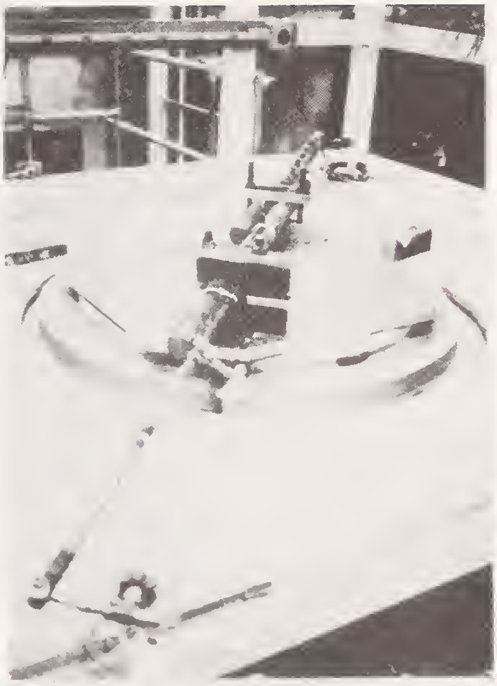
In order to determine the performance of the heat pipes in the bridge slab, a test slab was constructed and tested. The slab, figure 62, was 0.914 x 2.13 m x 19 cm (3 x 7 ft x 7.5 inch). The heat pipes were inserted on 22.9 cm (9 inch) centers from both sides as shown in the figure. Only four of the eight pipes were charged with ammonia. The only purpose of the four others was to provide structural symmetry in the slab. Steel rebars were spaced as shown in figure 63, and a 1-2-4 concrete mix was poured in accordance with accepted highway practice, figure 64.

After the concrete had set for two weeks, the entire slab was insulated with 5 cm (2 inch) of fiberglass insulation, figure 65, and a tare test was run to evaluate the insulation effectiveness. Thirty watts was applied to each pipe, and the temperature of the slab was monitored. The steady increase of temperature after several hours indicated that insulation losses would not significantly affect test results.

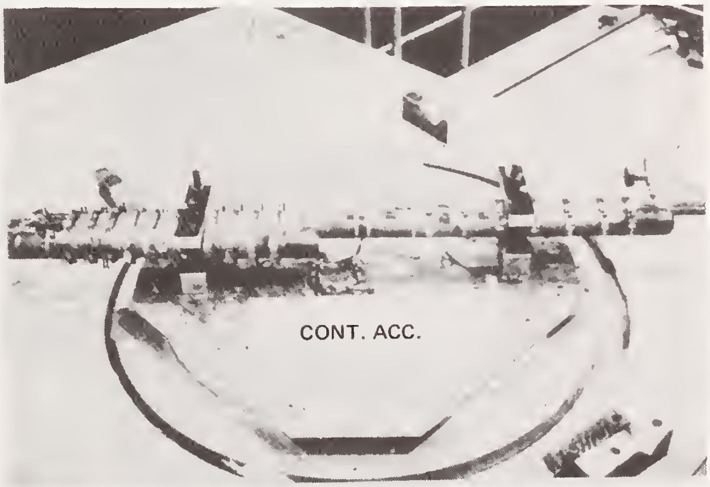
Again, as requested by FHWA, two sets of thermal tests were run: one before and one after a vibration test. For the vibration test, the slab was set up as shown in figure 66, with a hydraulic vibrator underneath the center. Both ends were supported on air-spring pads (Firestone air bags). The vibration test was run for one hour, at 20 Hz, at an average level of 1.2 g. No cracking was observed in the slab, and the thermal test results before and after vibration were similar.



SPECIMEN 1

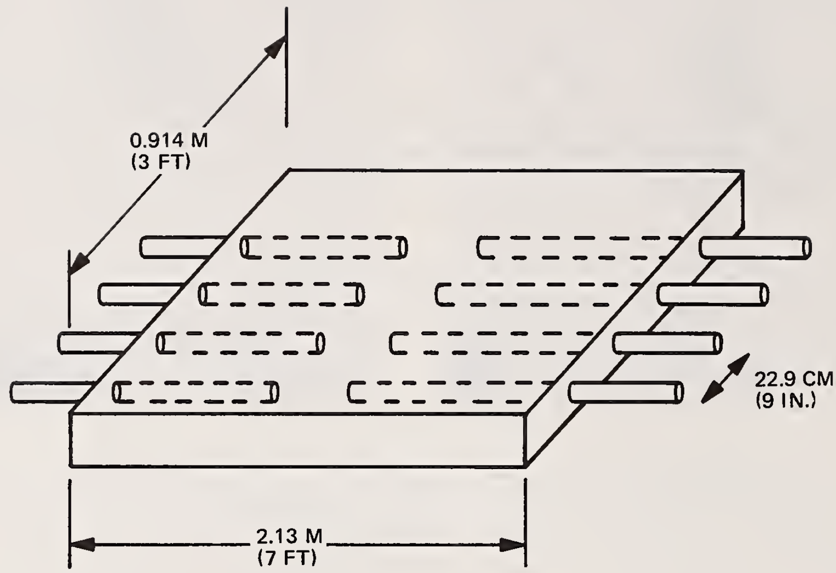


SPECIMEN 3



SPECIMEN 2

Figure 61 Heat pipe joints under test



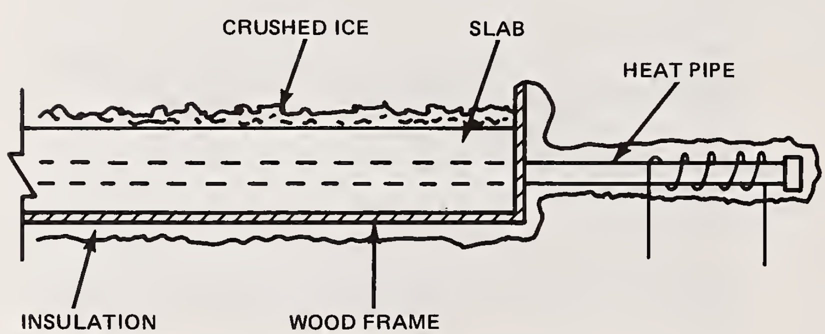


Figure 62 Bridge heat pipe/slab test

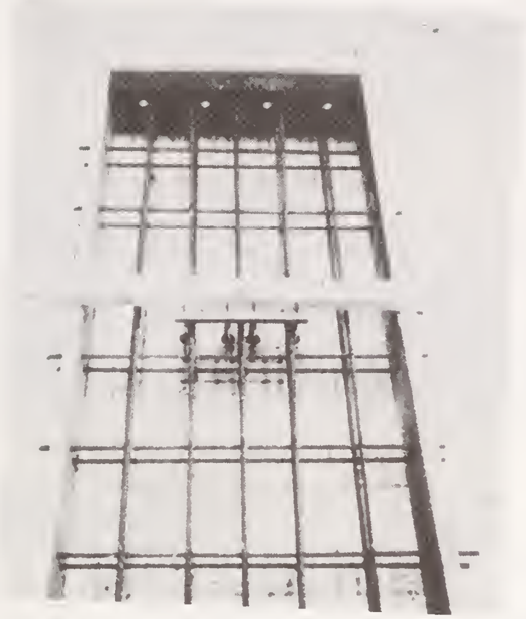


Figure 63 Concrete slab showing re-rods

Figure 64 Concrete slab

The first thermal test runs were performed at room temperature, with the top surface exposed to the air. A fan was used to blow air over the surface, figure 67. A load of 46 watts was applied to each of the pipes, and the slab allowed to reach steady state (which took about an hour). Results of these tests, before and after vibration testing, are presented in figures 68 and 69. For comparison, earlier, analytical results are shown in figures 70 and 71, Reference 3.

The comparison of test and analytic results is summarized in table 15. Although there are a few differences between initial test and analytic conditions, the results are comparable. The analytical procedure was based on an overall temperature difference between the heat pipe and the air of 8.33°C (15°F); however, based on the power-input and environmental conditions, a temperature difference of 6.11 to 6.67°C (11 to 12°F) was measured in the test program. Since this temperature difference is close to the analytical assumption, the temperature drop between the heat pipe and the slab surface can be compared for both cases. As shown, the analytical results were 6.11 and 7.2°C (11 and 13°F) for heat pipes spread on 15.24 cm (6 inch) and 30.48 cm (12 inch) centers, respectively. For the test slab with heat pipes on 22.9 cm (9 inch) centers, corresponding values were 5.2°C (9.33°F); this test result compares favorably to the analytical predictions. The slightly lower temperature difference achieved in the test is expected, since the overall temperature difference from the heat pipe to the air was less in this case. In both cases the surface temperature was about 1°C above air temperature, also a good correlation with analytical predictions.

After the room temperature tests were run, the tests were repeated at the same power level, except with a 5 cm (2 inch) layer of crushed ice used to cool the surface to near freezing. The tests were run for two hours, with final results as shown in figures 72 and 73. The difference between the heat pipe to surface ΔT in these tests and in the dry room temperature tests indicates that steady state had not been reached in the wet tests; since this test attempted to cool the slab significantly below room temperature, this result was not unexpected. However, the surface temperature, which varies from 1.6 to 3.9°C above freezing (ice temperature), does indicate that the concrete is capable of transferring heat quickly enough to prevent even local surface subcooling.

Since these results were in good agreement with the earlier analytical work, the bridge model portion of the analytical model was judged acceptable.

2.6.5 Test Conclusions

Tests were performed to measure four critical parameters:

- The ability of the earth to provide the hourly and annual energy demand required
- The ability of a valved heat pipe to control the amount of energy removed from the earth

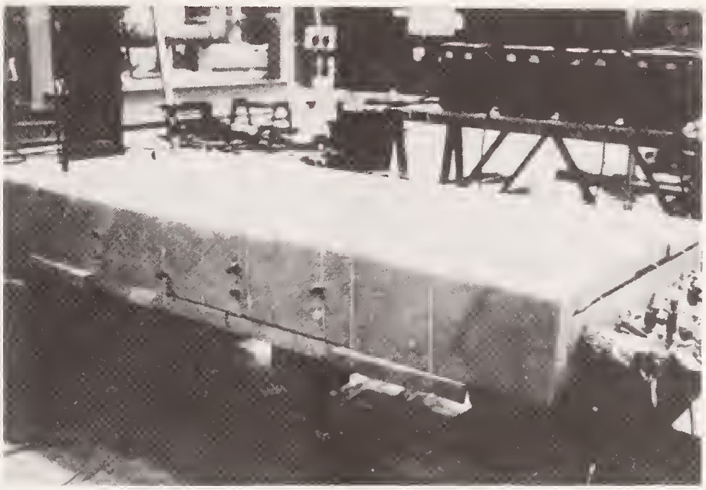


Figure 65 Thermal performance — tare

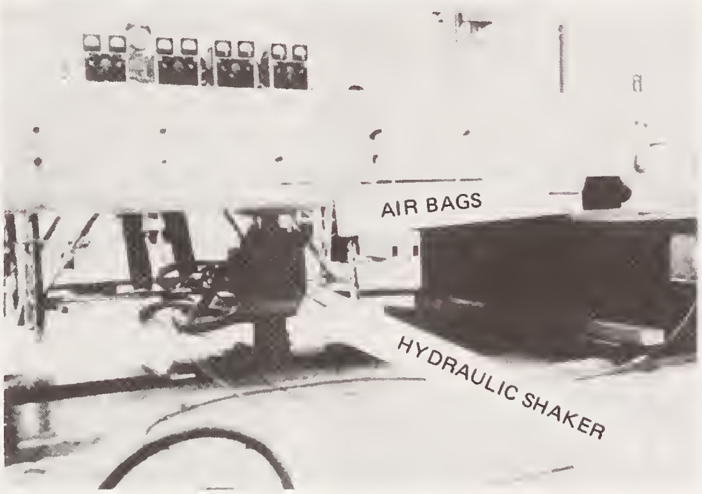


Figure 66 Vibration setup

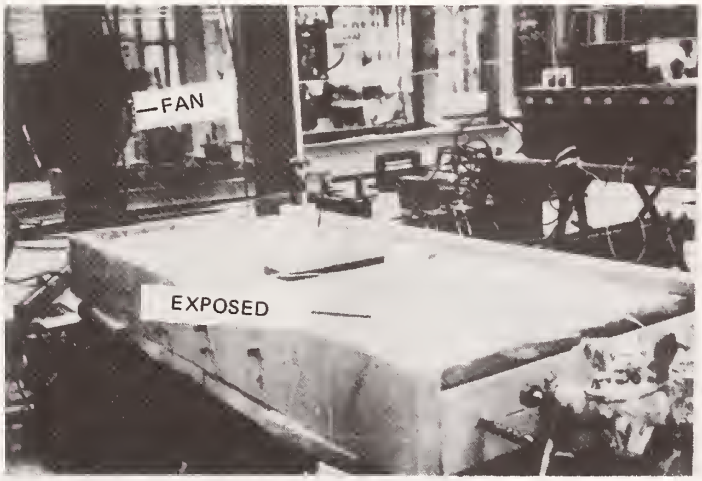


Figure 67 Thermal performance — dry

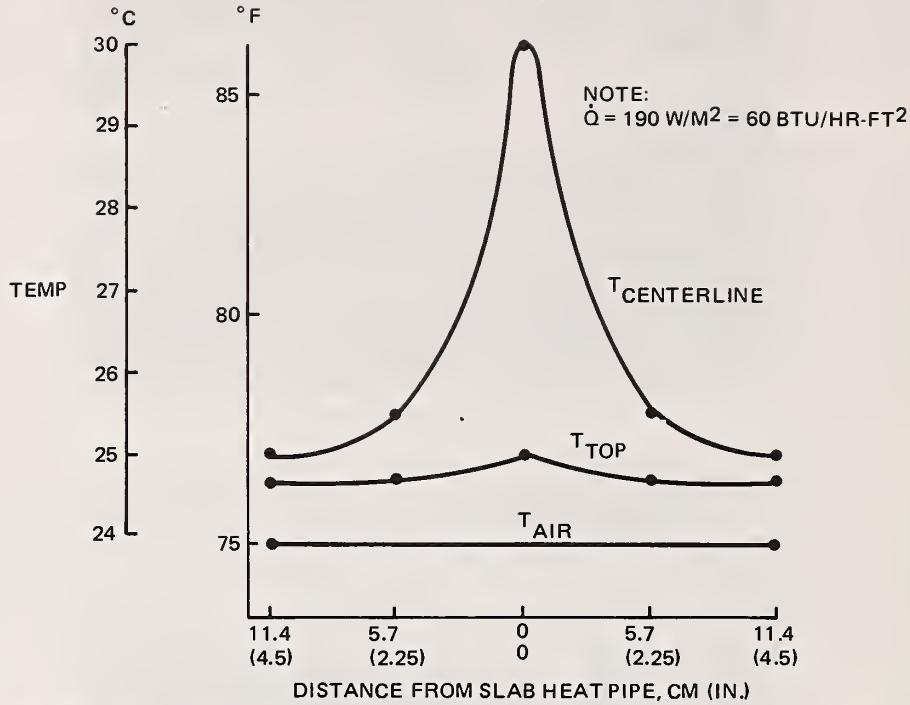


Figure 68 Response of concrete slab one hour after power is applied — dry, bare top surface before vibration test

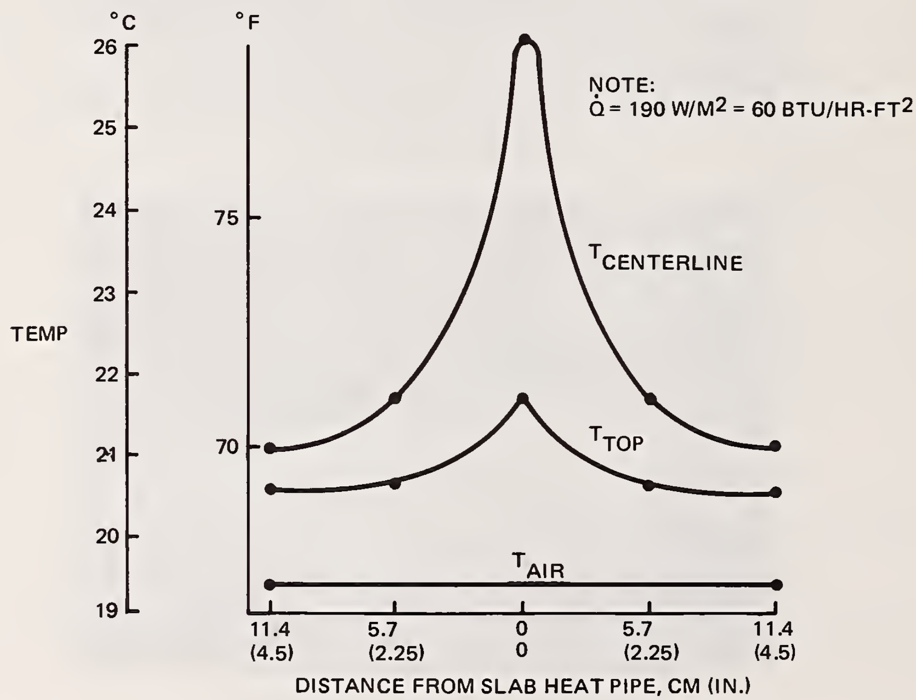


Figure 69 Response of concrete slab one hour after power is applied — dry, bare top surface after vibration test

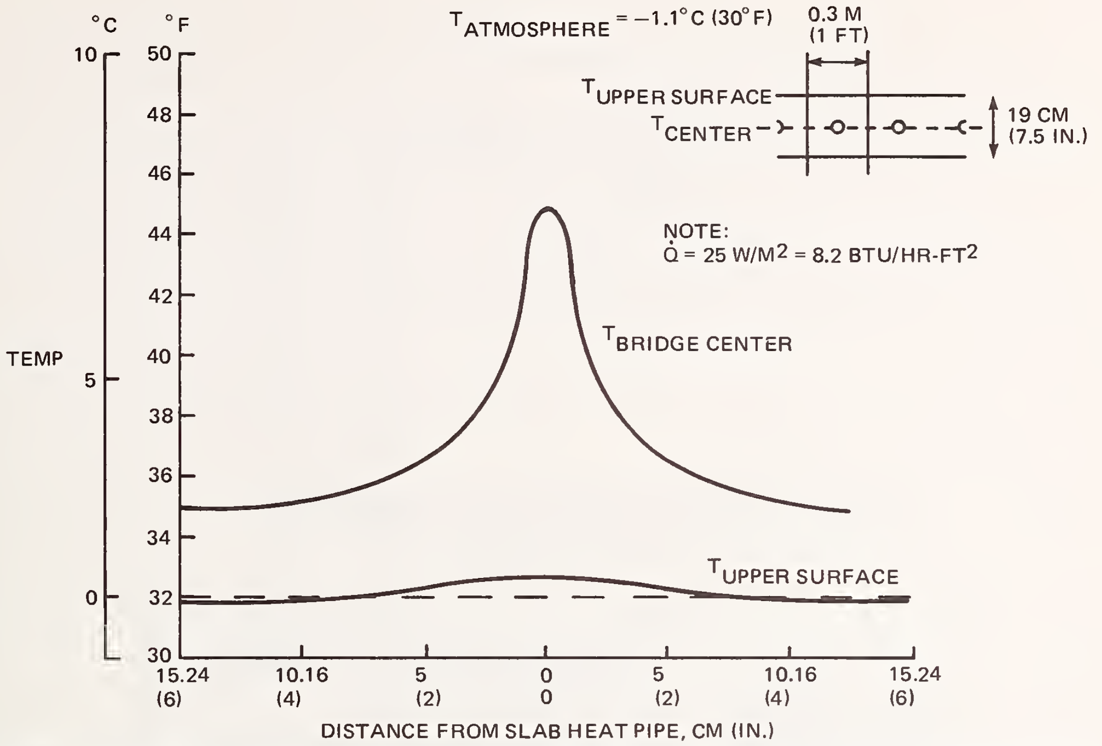


Figure 70 **Steady state response of bridge deck with heat pipes on 0.3 m (1 ft) centers, heat pipe temperature = 7.2°C (45°F) — from computer model**

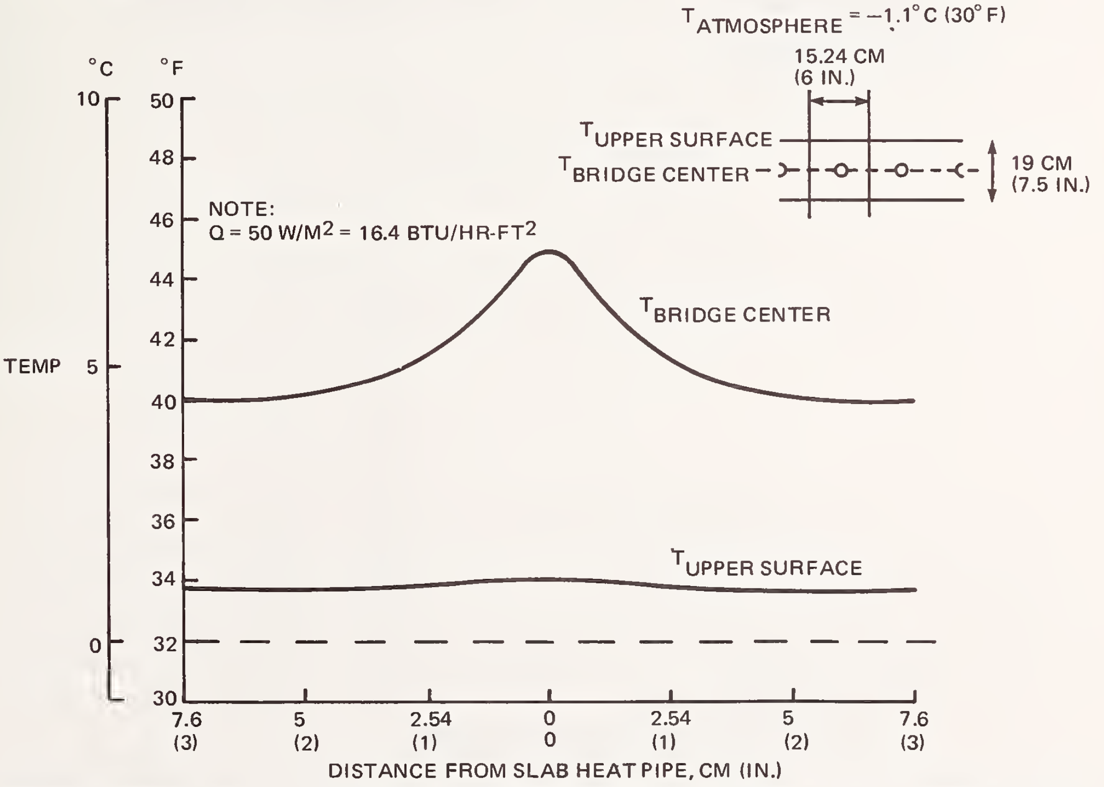


Figure 71 **Steady state response of bridge deck with heat pipes on 15.24 cm (6 inch) centers, heat pipe temperature = 7.2°C (45°F) — from computer model**

Table 15 A Comparison of Experimental and Analytical Results for Concrete Slabs

Result	Heat Pipe to Air ΔT		Heat Pipe to Avg Surface ΔT	
	°C	°F	°C	°F
6-In. Case (Analytic)	8.33	15	6.11	11
12-In. Case (Analytic)	8.33	15	7.2	13
9-In. Case (Experimental, Before Vibration Test)	6.11	11	5.2	9.33
9-In. Case (Experimental, After Vibration Test)	6.67	12	5.2	9.33

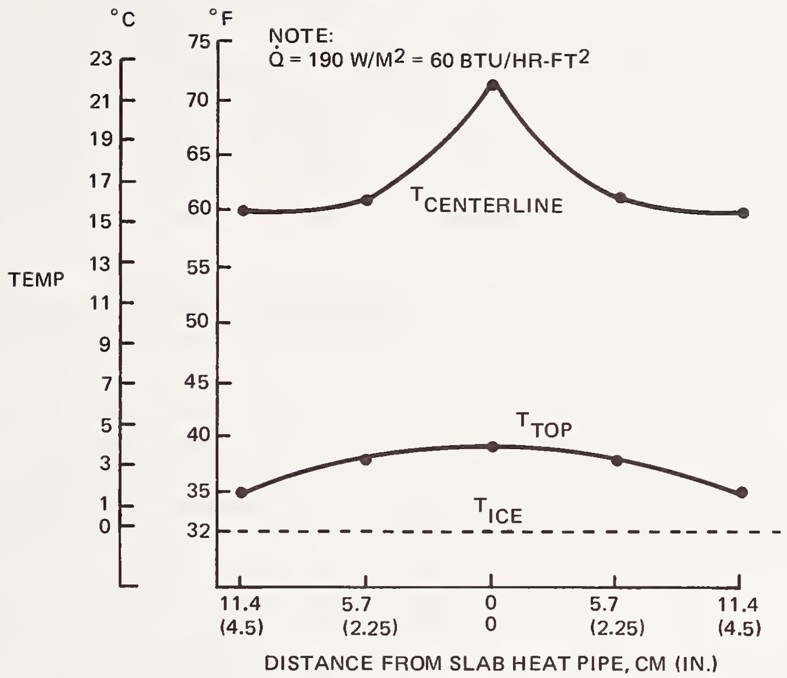


Figure 72 Response of concrete slab 2 hours after power is applied and 5 cm (2 inches) of ice is placed on surface, before vibration test

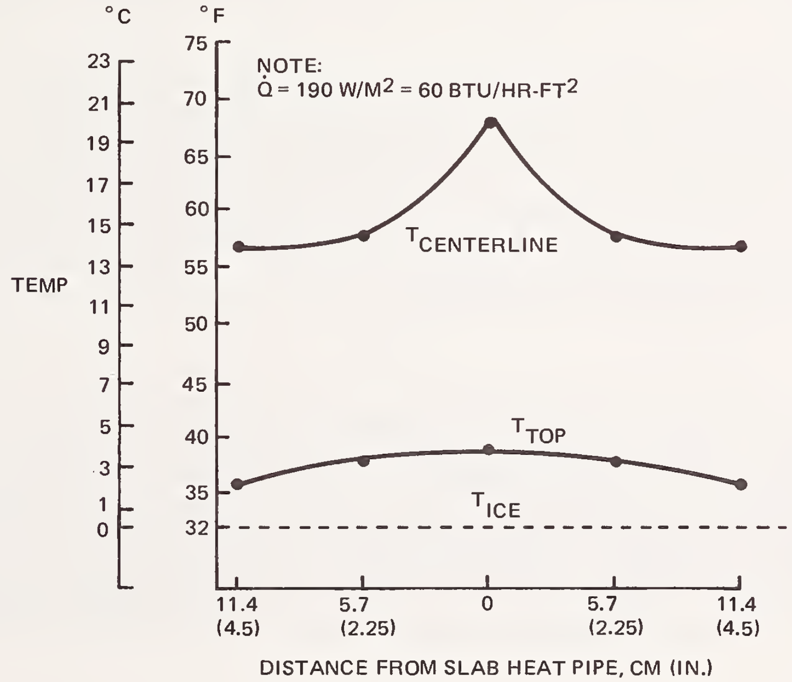


Figure 73 Response of concrete slab 2 hours after power is applied and 5 cm (2 inches) of ice is placed on surface, after vibration test

- The temperature drop across heat pipe joints
- The temperature drop from the bridge heat pipes through the deck slab.

The earth heat pipe test results correlated well with the analytical results, and thus verified the ability of 2 inch, nominal, heat pipes to extract energy from the earth at the rate required to prevent preferential icing. The selected design thus is suitable for system operation. Tests performed on the valved heat pipe indicated that the presence of the valve does not impair pressure integrity of the pipe and that the valve can effectively shut off the pipe, when desired.

The slab test results, like the heat pipe test results, correlated well with the analytical predictions of temperature drop from the bridge heat pipes to the slab surface.

The major finding of this test effort, however, was that low-cost, heat pipe to heat pipe joint conductances would be inefficient, and would require excessively long joint lengths to maintain the temperature drop across the system at an acceptable level. Moreover, the length of heat pipe joints affects the overall design in several ways: for earth heat pipes, the need for a long joint length may require increased spacing between the pipes and require that additional land area be provided. In addition, the length of the joint directly increases the length of the header heat pipe required; since these heat pipes already require flexible sections in order to be transportable, this factor is of vital concern. Finally, the requirement for long connections between the bridge and header heat pipes would complicate the installation of the system in an actual bridge deck.

The negative joint test results indicated that a totally passive heat pipe system cannot be applied economically to highway bridge decks. The elevated level of the bridge deck makes it impractical to connect earth heat pipes directly into the slab, as has been considered for highway surfaces; and the poor performance of heat pipe connections requires either excessively long joints or use of an excessive number of earth and header heat pipes. Although development of a more efficient joint design may be possible, its complexity and cost would probably be prohibitive.

As an alternate approach, a pumped fluid loop might connect the earth and bridge heat pipes more efficiently, and at a lower cost than the header heat pipe system. Moreover, this design retains the reliability of the heat pipes by making use of the pumped loop system only to carry the energy from the earth heat pipes to the bridge heat pipes; hence, if a single heat pipe fails, only a small percentage of the total system performance is lost. Access to the pumped loop system can be provided for service in the event of pump failures, line leaks, etc. The use of a pumped fluid loop also minimizes the number of pipes that must be brought up the bridge pilings, and eliminates

some of the design constraints imposed by the necessity to provide a favorable tilt (evaporator lower than the condenser) for the header heat pipe installation. This system also eliminates the need for valved headers, since the pump would perform this function. For these reasons, use of a pumped fluid loop is recommended for connecting the earth and bridge heat pipes.

2.7 FINAL DESIGN DETAILS

An earth heat pipe system for preventing the preferential freezing of a typical highway bridge deck was laid out on the basis of the analytic and test results. The system uses earth and bridge heat pipes to extract the earth energy and distribute it in the deck slab; a water/glycol pumped loop system is used to connect the earth and bridge heat pipes. Based on analytical results, 1 metre of 2 inch, nominal, earth heat pipe is provided for every 0.3 square metre of deck surface and half-inch, nominal, heat pipes are installed at the bridge slab midplane on 22.9 cm (9 inch) centers to distribute the heat. The description of the general procedure used to define this system should enable highway engineers to size similar systems for alternate locations and bridges.

2.7.1 Baseline Design - Typical Installation

Figure 74 shows the recommended point design configuration for a typical bridge located in New York City. The bridge considered consists of a 15.3 m (50 ft) wide by 30.5 m (100 ft) long exposed surface with crowned roadway. Based on design requirements, 1524 m (5000 ft) of earth heat pipes or 77, 2 inch, nominal, heat pipes inserted 19.8 m (65 ft) into the ground would be required. Each of these pipes would supply 1.14 kw (3900 Btu/hr) or (0.189 kw/m^2 x 464 m^2/77) pipes ([60 Btu/hr-ft^2 x 5000 ft^2]/ 77 pipes) under maximum load. The bridge heat pipes are inserted from both edges of the bridge such that the desired total tilt of 5 cm (2 inches) is included in the design. In order to minimize system temperature drops, a finned tube heat exchanger is attached to the top of the earth heat pipes and outer (condenser) ends of the bridge heat pipes to transfer the load from the earth heat pipes to the fluid loop, and from the loop to the bridge heat pipes. Based on analytic evaluations, each of the bridge heat pipes should carry a maximum load of 0.33 kwh (1125 Btu/hr) or 0.189 kw/m^2 x 0.228 m x 7.65 cm (60 Btu/hr-ft^2 x 9/12 ft x 25 ft).

Several heat exchanger manufacturers that were contacted have indicated that a fluid/heat pipe heat exchanger suitable for our requirements can be purchased at a reasonable cost. The finned, double-tube heat exchanger that is likely to be purchased, figure 75, can be welded to the pipe used to manufacture the earth and bridge heat pipes. Mechanical fittings attached to the heat exchanger would simplify connecting the earth and bridge heat pipes to the fluid loop.

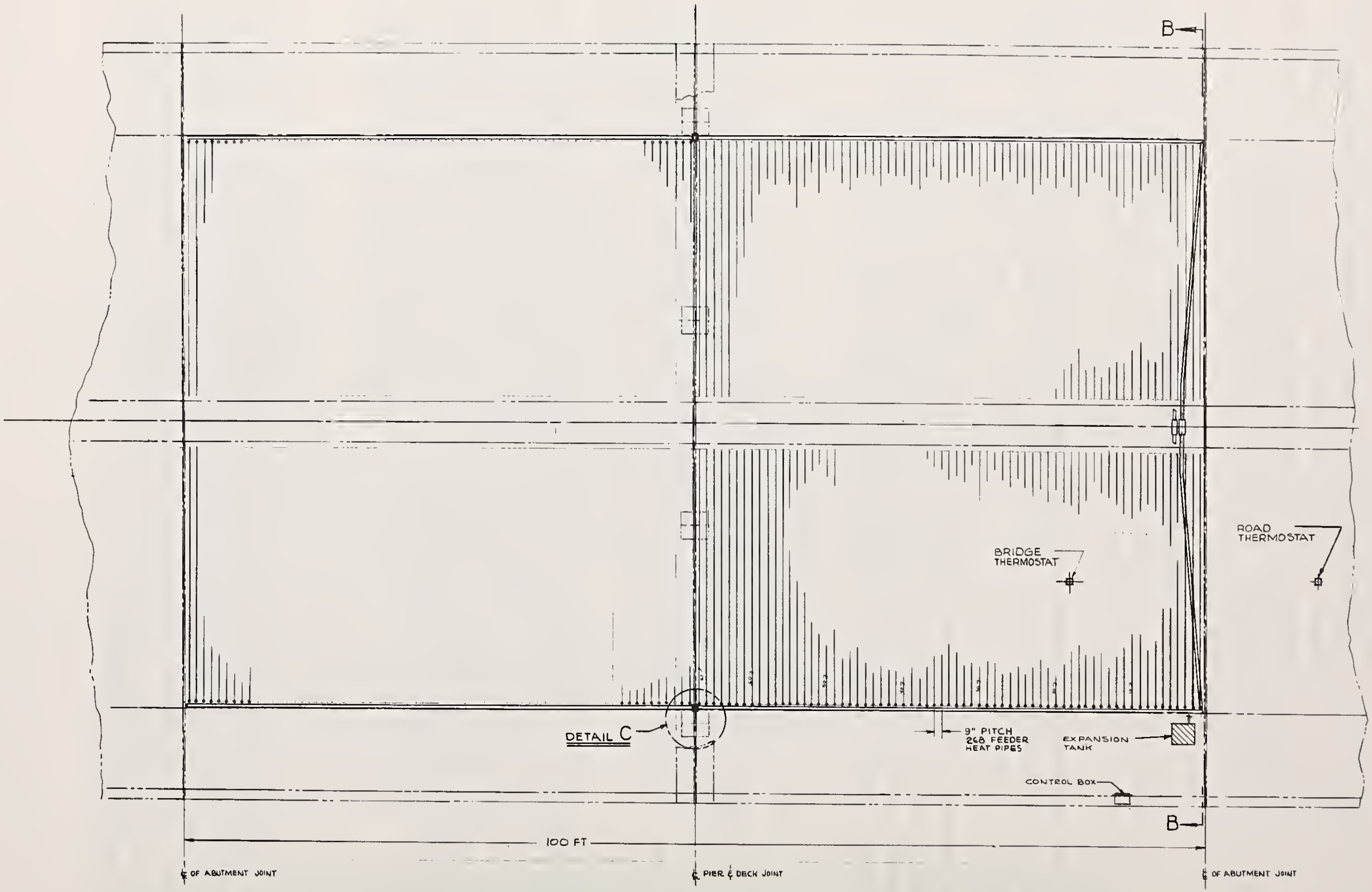


Figure 74 Bridge heat pipe installation (new bridge), sheet 1 of 3

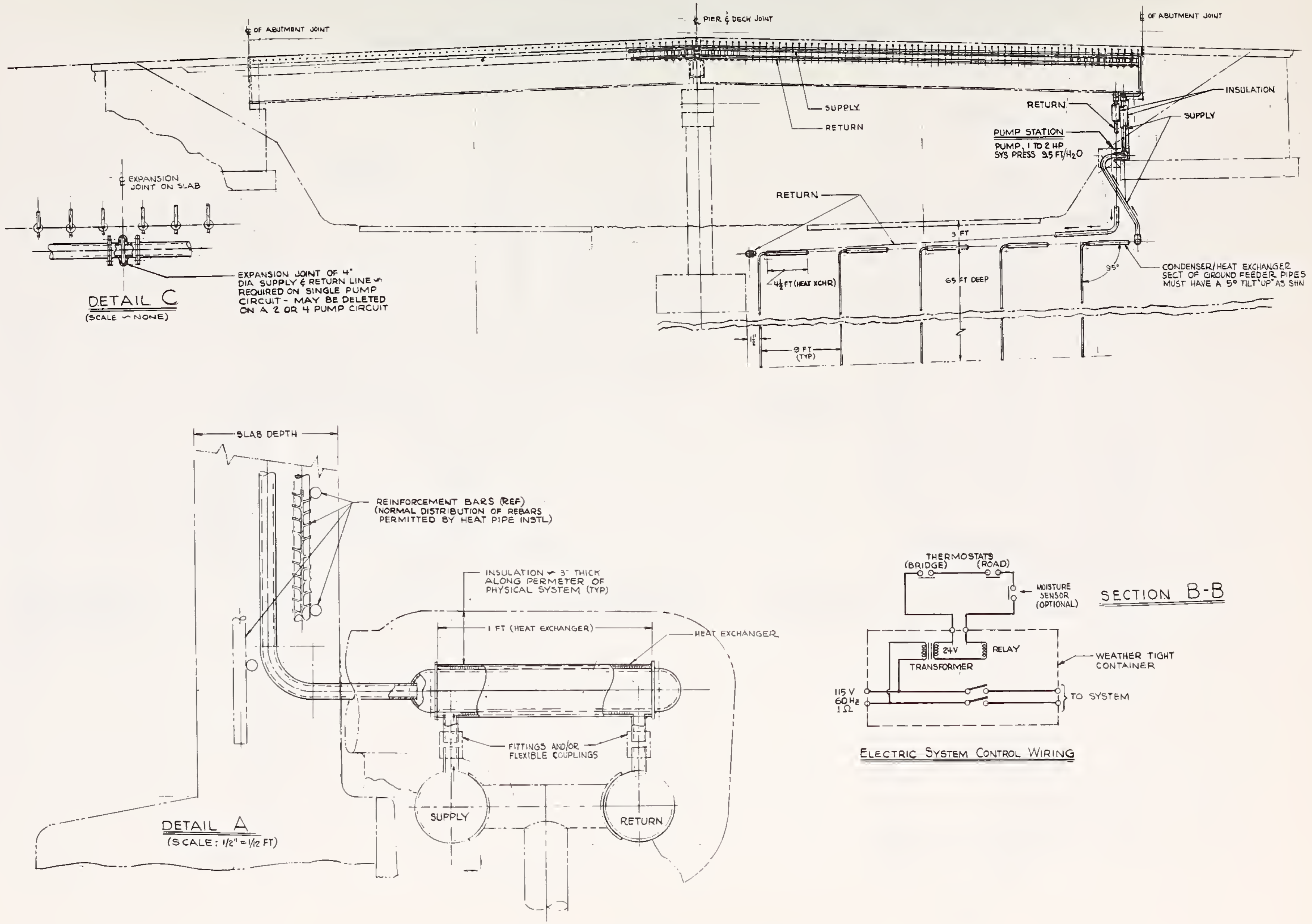


Figure 74 Bridge heat pipe installation (new bridge), sheet 2 of 3

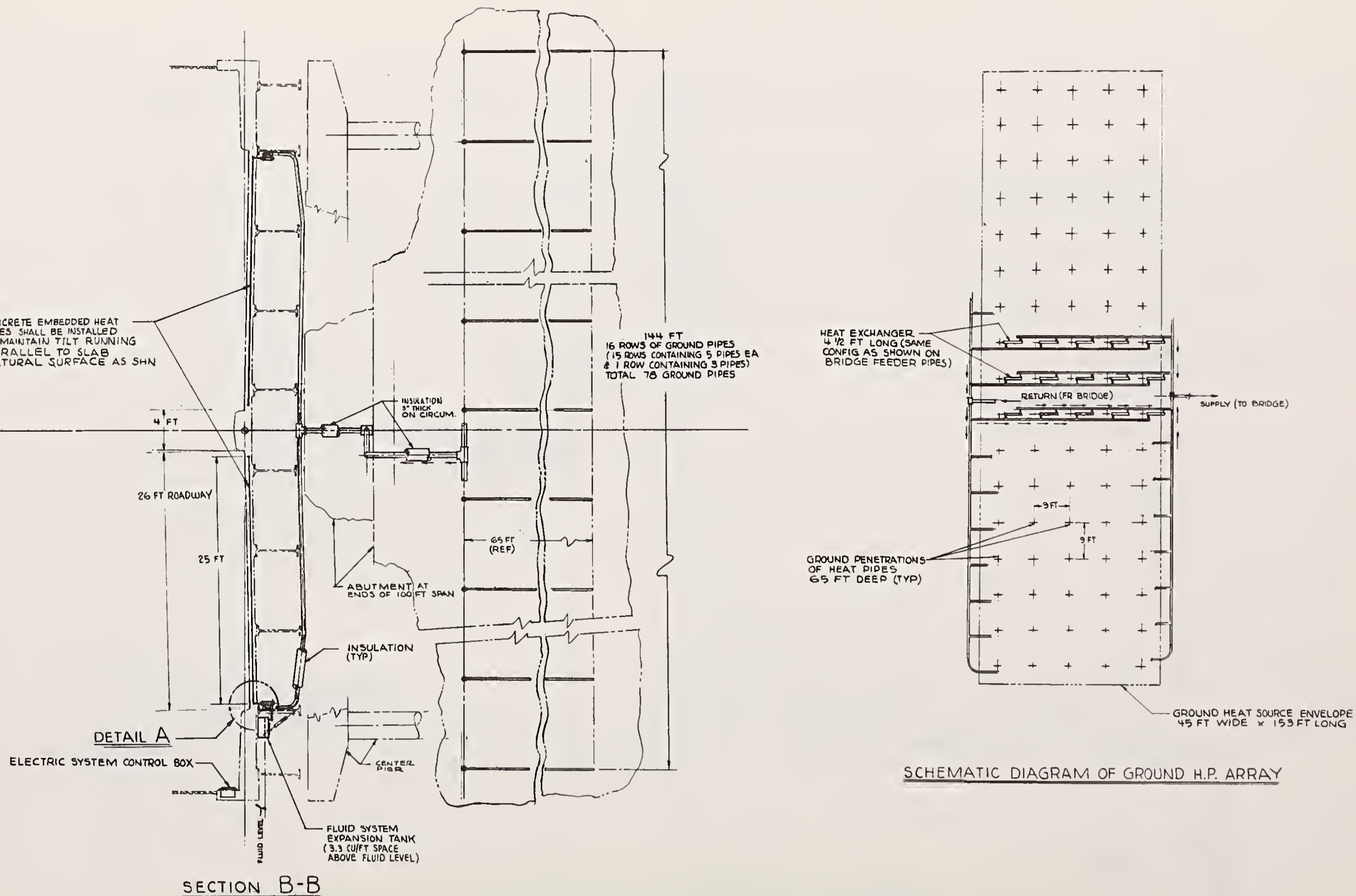


Figure 74 Bridge heat pipe installation (new bridge), sheet 3 of 3

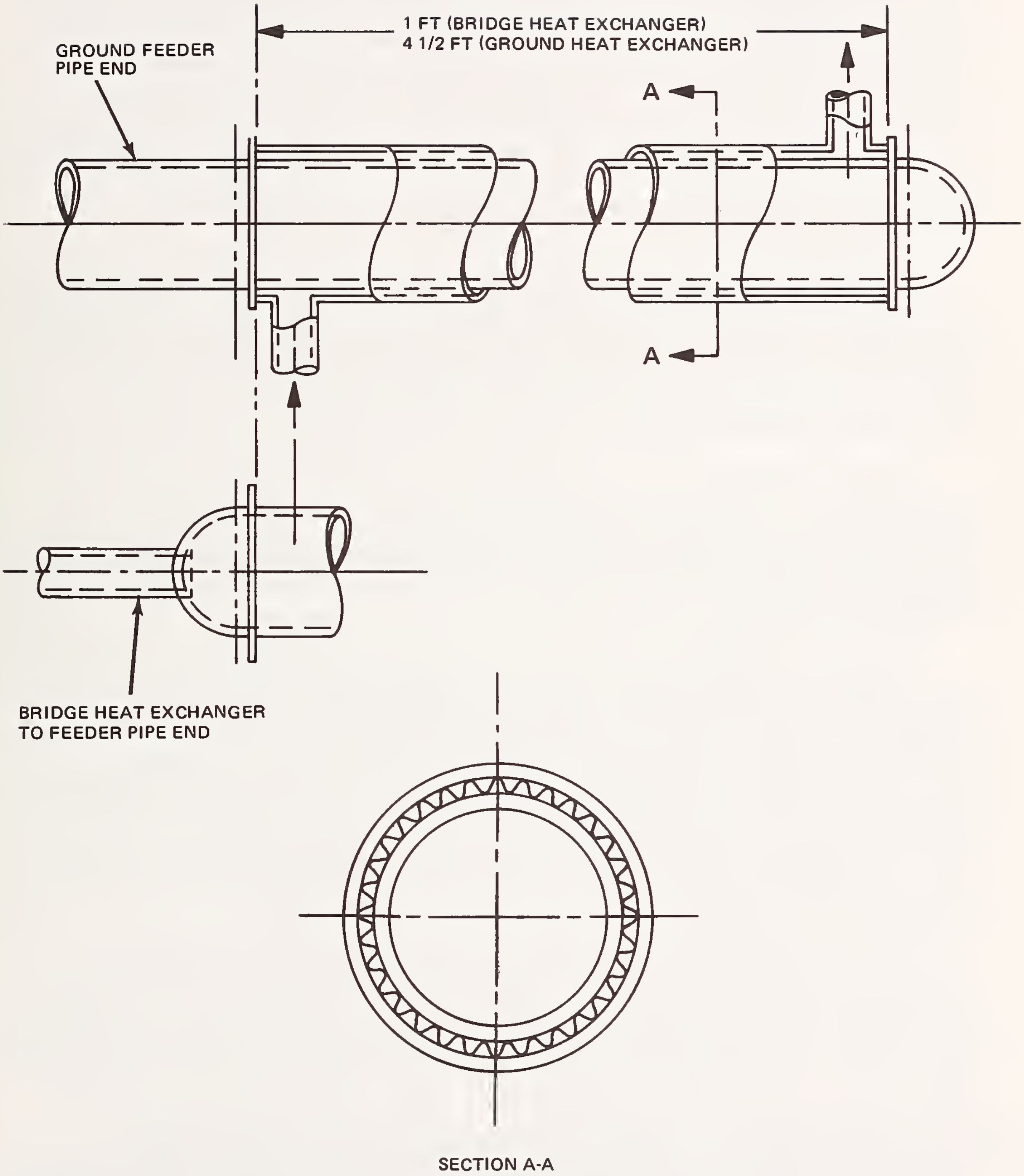


Figure 75 Finned, double tube heat exchanger

The same basic heat exchanger design is suitable for both the bridge and earth heat pipes. This design, which has been developed with the assistance of the Lytron Corporation, a major manufacturer of finned heat exchangers, should provide an overall heat transfer coefficient (UA) of 90 w/°C (400 Btu/hr-°F) between the pumped loop fluid and heat pipe vapor per metre (foot) of heat exchanger, with a pressure drop of 0.061 kg/cm^2 per metre (0.3 psi per foot) of heat exchanger, for a fluid (ethelene glycol/water) flow rate of 11 litres/minute (3 gpm). If a 2 inch, nominal, inner pipe were used for the bridge heat pipe connection, a transition section would be required to mate with the 0.5 inch, nominal, bridge heat pipes; but such a transition would decrease the heat exchanger length required. Moreover, if the same basic design could be used for the bridge and earth heat exchanger, these units should be available at a lower cost.

The pumped loop system is designed to use a 50/50 ethelene glycol-water mixture, such as NUTEK 800 which is available from the Nuclear Technology Corporation. This fluid contains an ingredient which will inhibit the galvanic corrosion which would otherwise take place between the aluminum fins and steel pipe; the corrosion rate of both metals thus should be limited to less than 0.002 mil/year, though the aluminum will corrode faster than the steel.

In order to decrease wall thickness and improve thermal performance, schedule 10 steel piping with a wall thickness of 0.279 cm (0.109 inch is used for the inner pipe. Although schedule 40 steel pipe is required for the earth and bridge heat pipes due to corrosion considerations, the fluid inhibitor will keep the corrosion rate at an acceptable level for the 20 to 30 year heat exchanger design life.

In order to isolate the loop from the environment, as well as protect it from vandalism, the connection from the earth heat pipes to the fluid loop is to be buried 0.9 to 1.2 m (3 to 4 ft) below the earth surface. This is accomplished by the construction crew first digging a trench 0.9 to 1.2 m (3 to 4 ft) deep and then drilling 10 cm (4 inch) holes to contain the earth heat pipes. At this point, the procedure varies, depending on the soil condition. Although the heat pipes may be inserted directly, a sleeve may have to be inserted in sandy soil in order to prevent the hole from collapsing. After the earth heat pipes are inserted, and the hole back-filled with the original soil, the pipe is bent so that the fluid loop connection can be made.

In order to minimize system pressure drops and, hence, pumping requirements, each of the earth and bridge heat pipes have been connected in parallel to the pumped loop system. This type of connection requires use of a supply and return fluid header. The system pipe layout is shown schematically in figure 76. In order that the coolant velocity be constant, 2 inch, nominal header pipes are used for the earth pipes, 4 inch, nominal, header pipes are used for the bridge, and 6 inch, nominal, pipes are used to connect the header and bridge pipes. Obviously, depending on the bridge design/configuration, one or more headers can be used to couple the earth and bridge heat pipes. Although, for simplicity, a single supply and return loop (and pump)

is assumed to be sufficient for the same application, more than one fluid loop and/or pumps can be used to increase reliability. In either event, the pump (pumps) should be placed in an enclosure above (or below) the ground to protect it from vandalism and to simplify maintenance. Although external corrosion of the buried pipe is not likely to be a problem for the desired 20 to 30 year design life, protection as well as insulation can be provided by standard commercial underground insulation, such as Gilso-Therm 70. This insulation can easily be applied since it is available in granular form, in cement-type bags, and can be poured directly into the trench surrounding the buried pipeline. The trench can be re-filled with soil, which acts as additional thermal insulation.

All exposed portions of the loop pipe and heat exchangers are to be wrapped with standard commercial pipe insulation of K = 0.043 W/m-°C (0.025 Btu/hr-ft-°F). The rate of energy loss as a function of pipe diameter is given in figure 77 for 7.6 cm (3 inch) thick insulation and a 11.1°C (20°F) temperature drop, from 10 to -1.1°C (50 to 30°F) from pipe surface to ambient. In the illustrated case, about 122 metres (400 ft) of 10.16 cm (4 inch) pipe and 30.5 m (100 ft) of 15.24 cm (6 inch) pipe are exposed. Therefore, in the worst case, an estimated 0.490 kw (1604 Btu/hr) is extracted from the loop due to insulation losses. An additional earth heat pipe in the system would easily compensate for these losses.

System pressure drops, and hence pumping requirements, are most affected by heat exchanger resistance to fluid flow. Moreover, the required size of the heat exchangers is dependent on the desired temperature drop through the units. The analysis presented indicates that the system can perform satisfactorily if the temperature drop, from the earth heat pipe condensers (top) to the bridge heat pipe evaporators (water end), is limited to about 2 to 3°C (5 to 6°F). This temperature drop can be divided among the bridge and earth heat pipe/fluid heat exchangers, as desired. If the length of the heat exchanger required for the bridge heat pipes were limited to about 30.48 cm (1 ft) to simplify installation, the overall temperature drop, from the fluid to the bridge heat pipes, would be 2.55°C (4.6°F) for the selected heat exchanger design; a design ΔT of about 0.555°C (1.0°F) thus would be available for the earth heat pipe/fluid loop connection. With this constraint, the earth heat pipe/pumped loop heat exchanger should be 1.37 m (4.5 ft). Based on these lengths, bridge and earth heat pipes would result in pressure drops of 0.02 and 0.1 kg/cm^2 (0.3 and 1.35 psi), or 0.693 and 3.11 ft of water, respectively. Since the lines and fittings shown in figure 74 should produce a pressure drop of 0.1743 kg/cm^2 (2.48 psi), or 175.57 cm (5.76 ft) of water, the total would be 0.2903 kg/cm^2 (4.13 psi), or 289.56 cm (9.5 ft) of water. This head can be provided by a commercial 1 to 2 horsepower pump, which will cost less than $200 to purchase and less than $20/yr to operate (based on 500 kwh and $0.04/kwh).

The total flow through the bridge and earth heat pipe heat exchangers must be equal. Since more bridge heat pipes are used than earth heat pipes in this design (268 vs 77), the fluid flow rate through each bridge heat exchanger must be less than through each

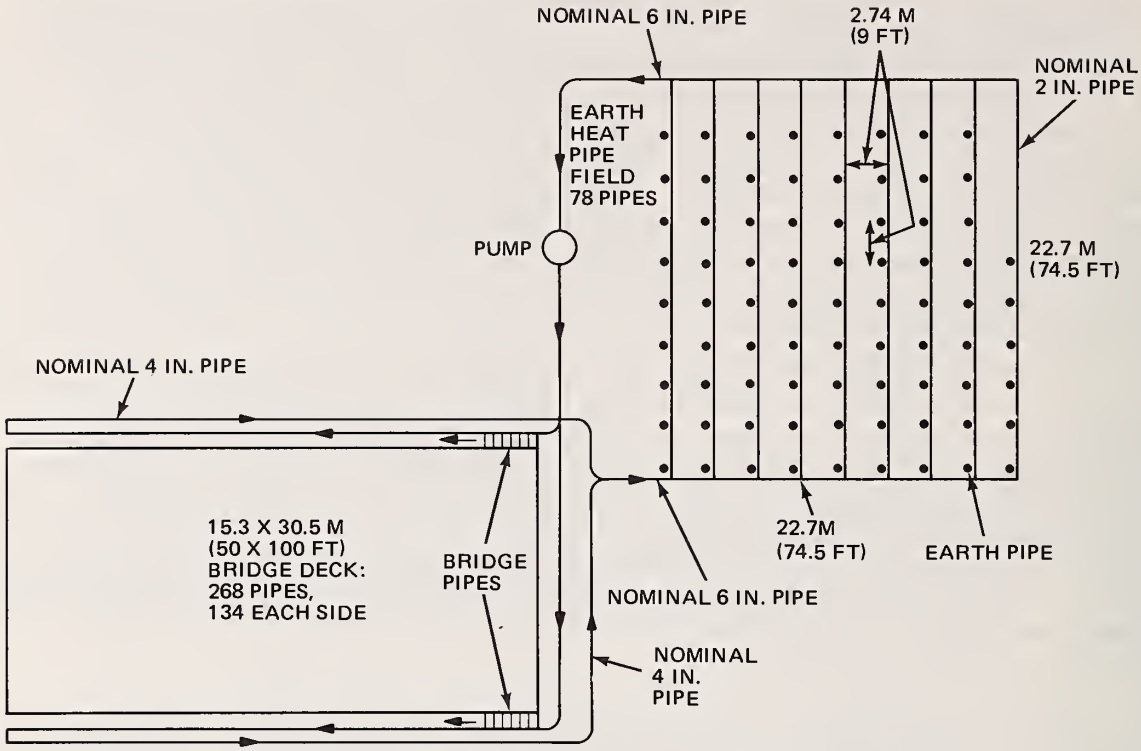


Figure 76 Schematic layout of earth heat pipe/pumped loop preferential bridge de-icing system

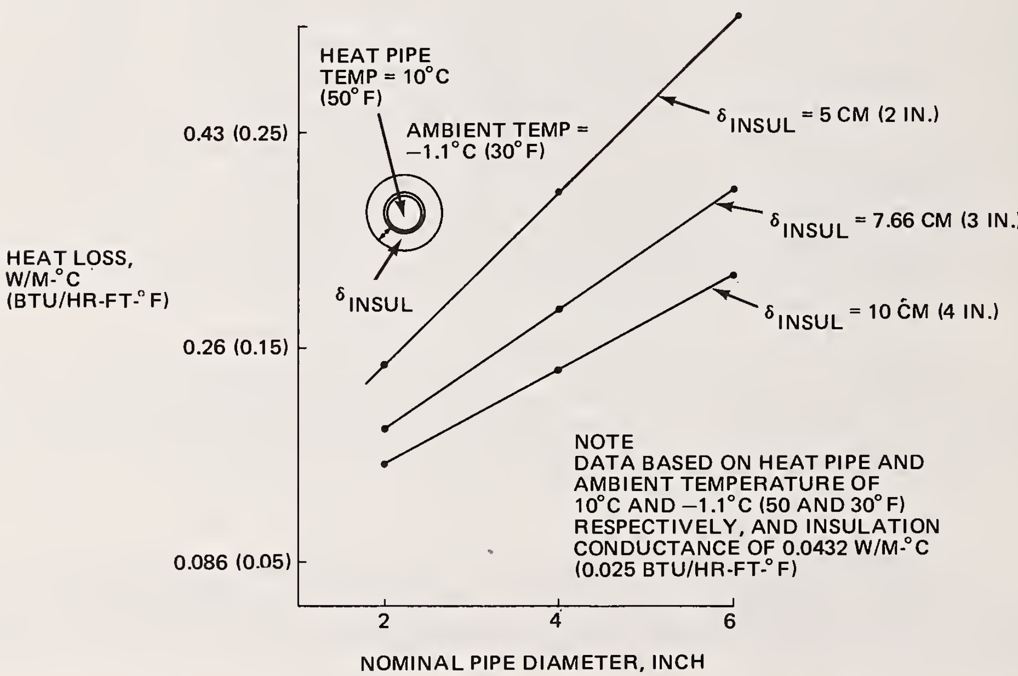


Figure 77 Environmental heat losses from insulated heat pipe

earth heat pipe exchanger; specifically, 3.26 vs 11.36 litre per minute (0.862 vs 3 gpm), respectively. Fortunately, consultation with Lytron Corporation indicated that the heat transfer coefficient in the bridge units can be maintained at this lower flow rate, at the expense of a small increase in pressure drop. For example, a double-pass unit in which flow enters and leaves the heat exchanger through one end of the unit can be built; obviously, the ΔP vs ΔT tradeoff will have to be optimized for each installation.

2.7.2 New Bridge Installation

The ability of an earth heat pipe system with 0.5 inch, nominal, low-carbon steel ammonia heat pipes on 9 inch centers to avoid preferential icing has been demonstrated. Obviously, as the earth simply represents a temperature (or energy/source), any other energy source such as electrical, fossil-fuel, or solar which results in similar bridge heat pipe temperatures will also perform satisfactorily. In fact, use of a higher temperature source should enable the spacing of the pipes in the bridge deck to be increased.

This analysis was based on locating the pipes at the slab mid plane. During the initial study phase, replacement of the reinforcing rods with heat pipes also seemed beneficial, since the rods have about the same spacing as that required for the bridge heat pipes and are close to the surface, 5 cm (2 inches) below the upper and lower deck surfaces. However, since FHWA bridge design personnel agreed with our consultant, Ammann and Whitney, that the existing structural configuration should be left intact at this stage of the investigations, the concept of replacing reinforcing rods with heat pipes was eliminated from consideration. That concept should be investigated further, after more experience is gained with this type of heat pipe system.

The effect of adding excessive steel to the bridge and the possibility of voids being created within the deck during the pouring of concrete was a source of some concern. Further study, though, indicated that if 0.5 inch, nominal, pipes were placed no closer than 15.2 cm (6 inches) apart, the concrete could be satisfactorily poured and the structural integrity of the deck would not be impaired. This fact, in addition to cost, influenced our decision to space the bridge heat pipes on 22.8 cm (9 inch) centers.

In order to avoid corrosion, the heat pipes should be either galvanized or coated with the same epoxy material (if any) used on the re-bars. The performance advantage of wicked heat pipes is small since they can pump a significant amount of heat "up-hill" only for heights of the order of a fraction of a centimeter. Since the cost of wicked heat pipes is significantly greater than that of no-wick, gravity assisted types, the latter were selected for the baseline design. However, this choice requires that each of the pipes be installed with the condenser higher than the evaporator. A tilt of about 5 degrees should be more than sufficient to assist liquid return.

The bridge heat pipes in the deck can either be installed across (perpendicular to) or in line with (in the same direction as) the traffic flow, depending on the bridge type and/or the designer's preference. If the roadway surface is crowned or sloped, the fluid loop headers could be installed along the outer edge of the bridge, as shown in figure 78. Headers for the crowned roadway surface would be located on both sides of the bridge deck, so that the bridge heat pipes could be installed with the proper tilt. The pipes would be located at about the slab mid-plane, and extend from one edge to the bridge center with a tilt of about 5 degrees. In the case of a sloped or graded roadway surface, figure 78, the bridge heat pipes would be installed so that the built-in tilt would assist heat pipe performance. Alternately, the bridge heat pipes could be installed in the direction of the traffic flow. For example, in the case of a narrow span or ramp of 6 to 12 m (20 to 40 ft), the earth heat pipes could be bent directly into the deck slab, as shown in figure 78. In this case, valves must be included for each of the earth heat pipes; the valve would be a natural break in the pipe which would permit the 2 inch, nominal, earth heat pipe to be connected to the 0.5 inch, nominal, bridge heat pipe. Since the requirement for additional valves would increase system cost and complexity, a pumped fluid loop could be used to connect the earth and bridge heat pipes, figure 74. In such a system, the bridge heat pipes would be installed with a tilt to provide return of liquid from the condenser. This installation would be especially desirable for bridges with a natural grade in the direction of traffic flow (uphill bridge).

Bridge heat pipes could also be installed with the traffic flow for longer span bridges, as shown in figure 78. In this installation the natural grade of the roadway can again be used to assist in gravity return of the fluid from the condenser to the evaporator. In any event, each of these designs makes use of 0.5 inch, nominal, low carbon steel ammonia heat pipes installed on 22.9 cm (9 inch) centers near the slab mid-plane.

The system heat pipes may be tied into the other steel members such as girders, floorbeams, or crossframes (generally near piers and abuttments) like those presently being built for bridge down-spouts. The final system design recommended in this report can generally avoid crossing expansion joints in the bridge by providing a heat transfer system on a span by span

basis. Expansion within a span could be absorbed by a flexible fitting placed between superstructure pipes and between substructures and pipes. If an expansion joint must be crossed, however, a bent, U-pipe configuration could be used, as is standard practice.

2.7.3 Existing Bridge Installation

The study of the feasibility of installing a heat pipe de-icing system on existing bridges considered the possibility of placing the pipes on the surface of the concrete deck under a bituminous overlay, or under the deck within an insulation blanket. Installing the heat pipes under a bituminous overlay would require the raising of bridge expansion dams, scuppers, and curbs. In addition, the concrete deck slab would have to be penetrated at several points to enable the heat pipes to be joined to the heat source. This penetration could adversely affect the structural integrity of the slab. Moreover, under constant traffic, the roadway riding surface would eventually follow the contour of the pipes (wash board effect) and produce a dangerous riding condition.

On the other hand, installation of heat pipes below the concrete deck does not seem economically practical. The heat pipes would have to be installed on close centers because of the increased temperature drop through the slab which significantly increases the number of pipes needed. Moreover, the multiple attachments to the underside of the deck slab that are needed to support the heat pipes could affect the strength of the slab. As a result of these problems, the heat pipe bridge de-icing system cannot be recommended for existing installations.

2.7.4 Additional Design Considerations

2.7.4.1 Corrosion

The rate of corrosion of steel pipes in the earth depends on the type of soil. Typical rates are shown in figure 79; 0.013 cm (0.005 inch) per year (5 mils) or less was selected as a design goal. At this rate, schedule 40, nominal, steel pipe would have a life of about 30 years. Pipe intended for installation where abnormally high corrosion rates may be expected will need further protection in the form of epoxy coatings and/or sacrificial anodes.

2.7.4.2 Heat Pipe Pressure Integrity

The operating pressure of the ammonia pipes is on the order of 0.3 kg/cm^2 (90 psi), which corresponds to a temperature of approximately 10°C (50°F); higher temperatures would be produced by summer pavement heating, and might occur during shipping and insertion of the pipes. The maximum design temperature of 93.3°C (200°F) would result in a design pressure of 56 kg/cm^2 (800 psi). With four times this value allowed as a safety margin, 225 kg/cm^2 (3200 psi) is the designed burst pressure. For a 2 inch, nominal, pipe, this requires a wall thickness of 0.045 cm (0.0177 inch), well within proposed design values.

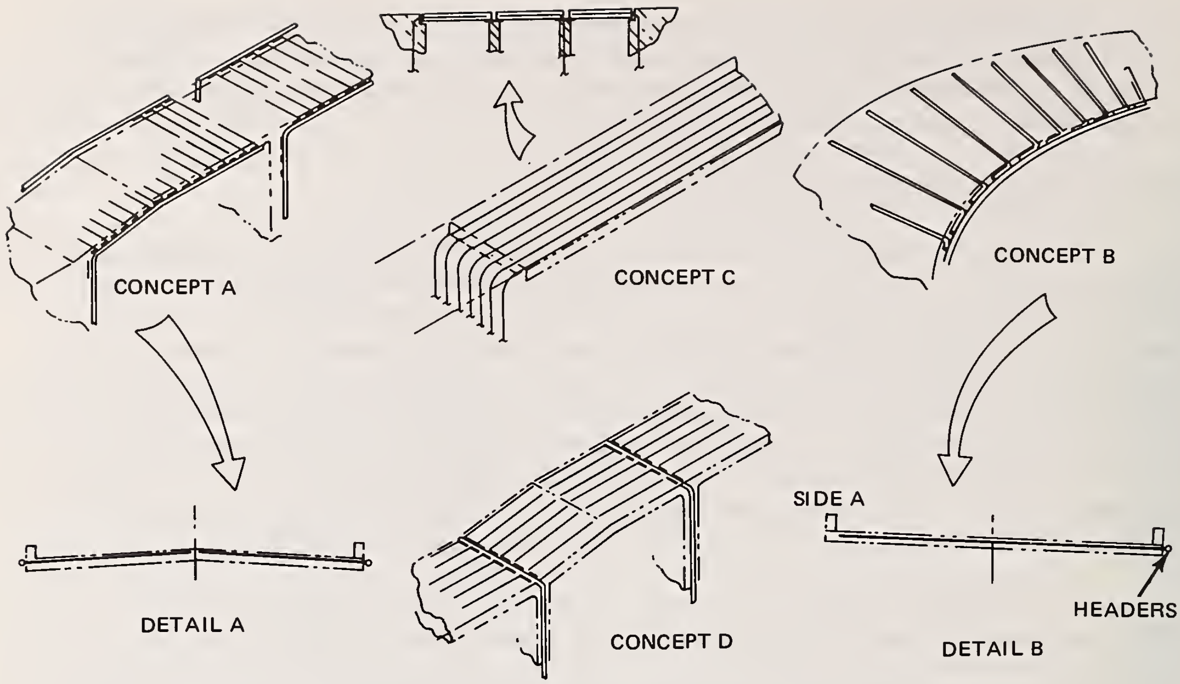


Figure 78 Alternate heat pipe installations into bridge for de-icing

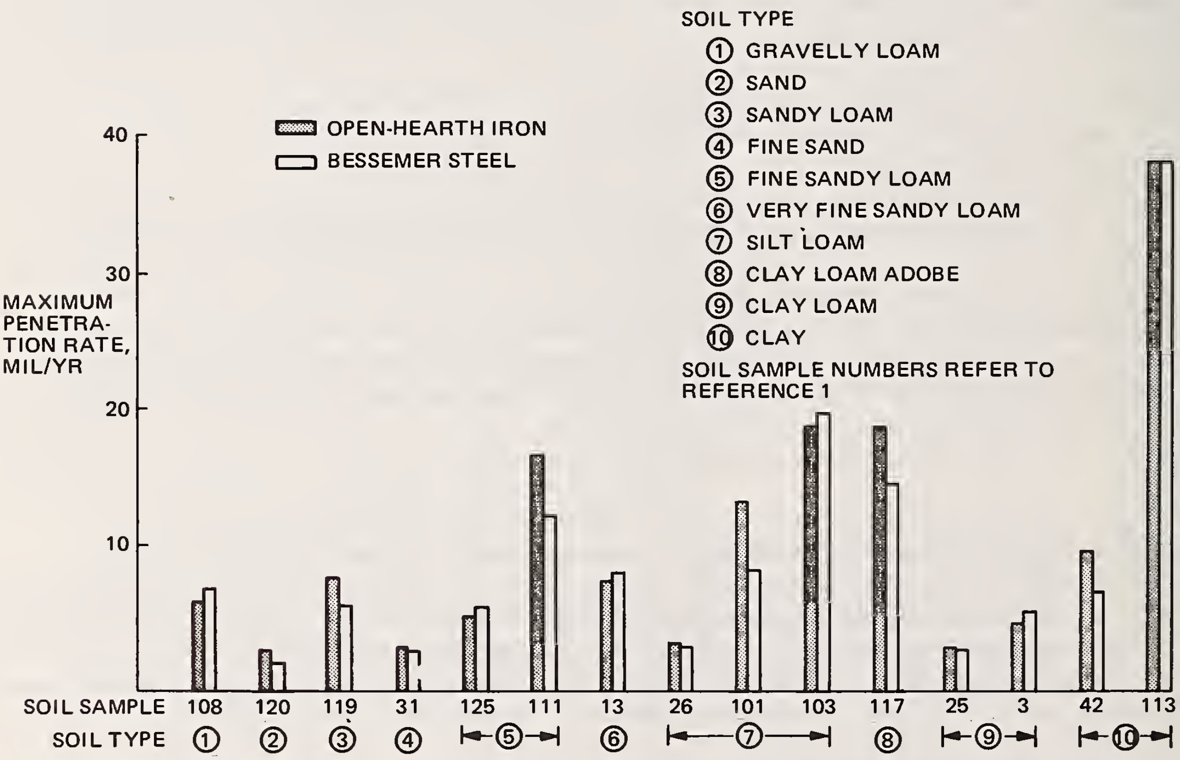


Figure 79 Average rates of maximum penetration of iron and steel for various soil types

2.7.4.3 Sensor Selection

The simplest control logic involves temperature sensors which turn the system off when the bridge deck is above freezing or above the road temperature. Thermostats have been selected as the temperature transducers for this logic. These devices feature low cost, excellent repeatability, compact size, and long life.

The thermostats, one each at the bridge and road surfaces, would be wired as shown in figure 80. Such a system would only be active if the road were above freezing; in practice, the system would activate in a near freezing event to allow time for heat to flow through the bridge deck. The hardware cost is estimated at about $250.

Annual system energy requirements can be further reduced by the use of humidity-dew point sensors. The humidity sensor would keep the system off on cold days, when the air has insufficient water to permit precipitation or condensation.

Two units that are available are capable of measuring dew point to the accuracy required by the system; the Brody Array hygrometer and the EG&G optical hygrometer. Both of these units provide a continuous signal in terms of percent relative humidity or dew point. The devices can be added to the temperature sensing system as shown in figure 80; including them would add about $400 to the total sensor package cost.

2.8 COST OF EARTH HEAT PIPE SYSTEM FOR AVOIDING PREFERENTIAL ICING

An initial estimate was made of the cost to install the earth heat pipe system on a typical 465 m^2 (5000 ft^2) bridge deck. Since system requirements are the same for the three sites under consideration, except for land area, the hardware and installation are nearly the same for each. In order to explore the possibility of economics of scale, the costs of a 1858 m^2 (20,000 ft^2) bridge also were evaluated.

Table 16 presents the results of this estimate. As shown in the table, cost is about \$102,050 or \$219.46/m^2 (\$20.41/ft^2) and \$357,000 or \$192.4/m^2 (\$17.85/ft^2) for the 465 and 1858 m^2 (5000 and 20,000 ft^2) bridges, respectively. The bridge and earth heat pipes represent the bulk of this cost, accounting for 62 percent of total system cost for a 465 m^2 (5000 ft^2) bridge. The pumped loop system represents 11.5 percent of the total system cost. The estimate was based on the assumption that component costs per area of bridge deck would be independent of bridge size and that assembly costs would decrease per area of deck with increasing bridge size.

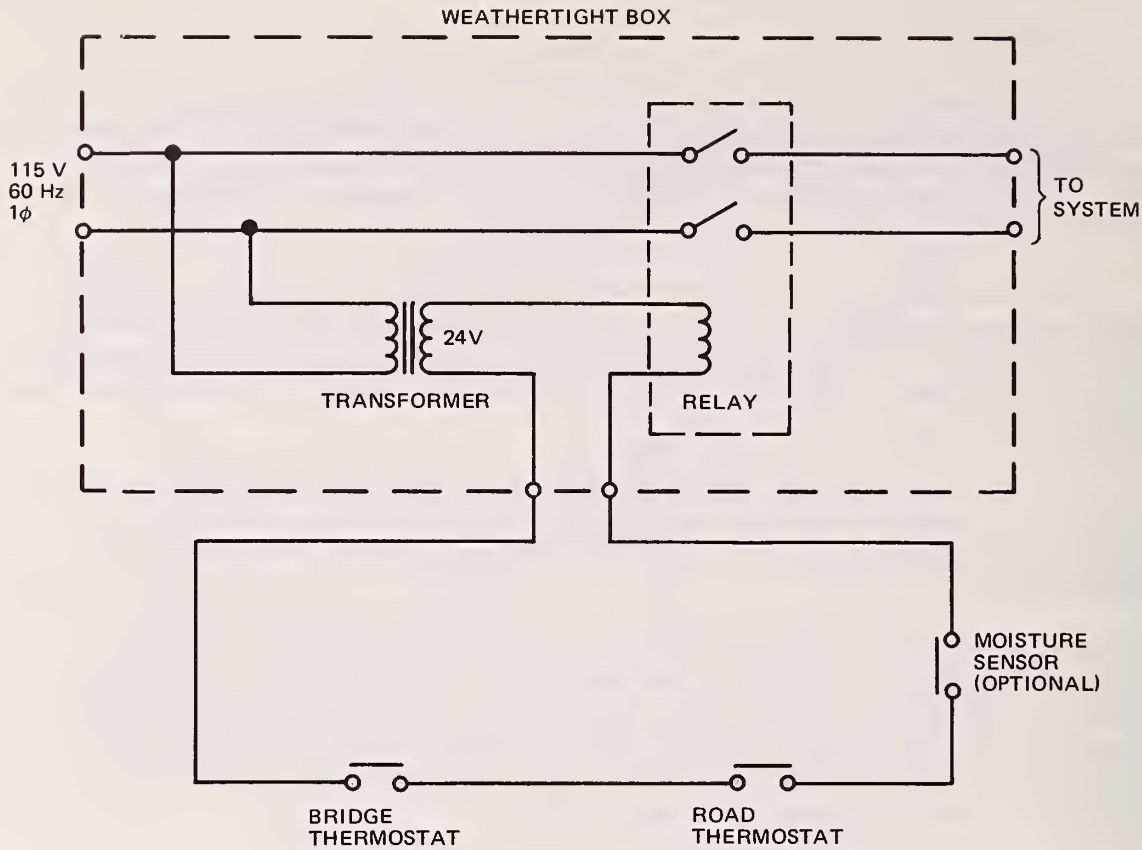


Figure 80 Electric system control wiring

Table 16 Estimated Costs of Earth Heat Pipe System

Item	Cost							
	465 m^2 (5000 ft^2)				1858 m^2 (20,000 ft^2)			
	Total $	$/m^2	$/ft^2	% of Total	Total $	$/m^2	$/ft^2	% of Total
Earth Heat Pipe ($350 each)	29,400	62.91	5.88	29	116,900	62.91	5.88	33
Bridge Pipes (Pumped Loop System)	33,500	72.04	6.70	33	133,500	71.85	6.20	37
Run-Around Loop								
Heat Exchangers ($25 each)	8,650	18.60	1.73	8	34,600	18.60	1.73	9
Pump; Tank, Insulation, Elbows	500	1.07	0.10	0.5	2,000	1.07	0.10	21
Wet Connections	3,500	7.53	0.70	3	14,000	7.53	0.70	4
Earth Insulation (11 tons)	1,500	3.23	0.30	1.5	6,000	3.23	0.30	2
Assembly	25,000	53.76	5.00	25	50,000	26.91	2.50	14
Total	102,050	219.46	20.41	100	357,000	192.14	17.85	100

Although the preliminary costs are in the same range as those for electrical and pumped loop de-icing systems which have already been installed, they are probably too high to encourage widespread use. System costs would have to be lowered to the $\$100/m^2$ to $\$160/m^2$ ($\$10/ft^2$ to $\$15/ft^2$) range to encourage general use; a cost of $\$200/m^2$ ($\$20/ft^2$) or more would probably limit its application to particularly hazardous locations. For comparative purposes, note that an initial earth heat pipe system which is being installed on a ramp in West Virginia will cost about $\$237/m^2$ ($\$22/ft^2$).

Various methods can be used to reduce system costs. The projection presented in this report is based on a relatively high cost estimate for installation of the earth and bridge heat pipes. Experience with the test pipes and the actual installation cost for the West Virginia system illustrates the need to obtain a faster and less expensive method of inserting heat pipes into the soil. If this is not possible, another approach to reduce system costs would be by augmenting or replacing the earth heat pipe with another energy source, such as solar or wind energy. The following paragraphs present a preliminary evaluation of a solar collector/heat pipe system for comparison purposes.

2.9 SOLAR COLLECTOR SYSTEM - PRELIMINARY EVALUATION

Solar energy is a renewable, natural energy source which may offer technical and economic advantages over an earth heat source. This preliminary investigation of a solar energy source thus was directed to a study of the system schematically described in figure 81; that system has a pumped fluid loop to collect the solar energy and store it within a tank, and another pumped fluid loop to transport the warmed fluid from the tank to the evaporators of the bridge heat pipes. The design requires a sensor/control system for both loops. Temperature sensors on the collector and within the tank activate the collector loop (A) only if the collector temperature is higher than the tank. The control system logic used to indicate the onset of preferential icing is used to activate the bridge heat pipe loop (B), and transport energy to the deck when required.

Water can be used as the transport fluid in both loops, if a drain-back design is employed to store the water in the underground insulated tank whenever the system is inactive. Alternately, a water-glycol mixture can be used if the lines are not drained of fluid during potential freezing conditions.

2.9.1 Design Considerations

Before a solar collector system can be designed, the following information must be obtained:

- Amount of energy required per icing event
- Annual energy requirement

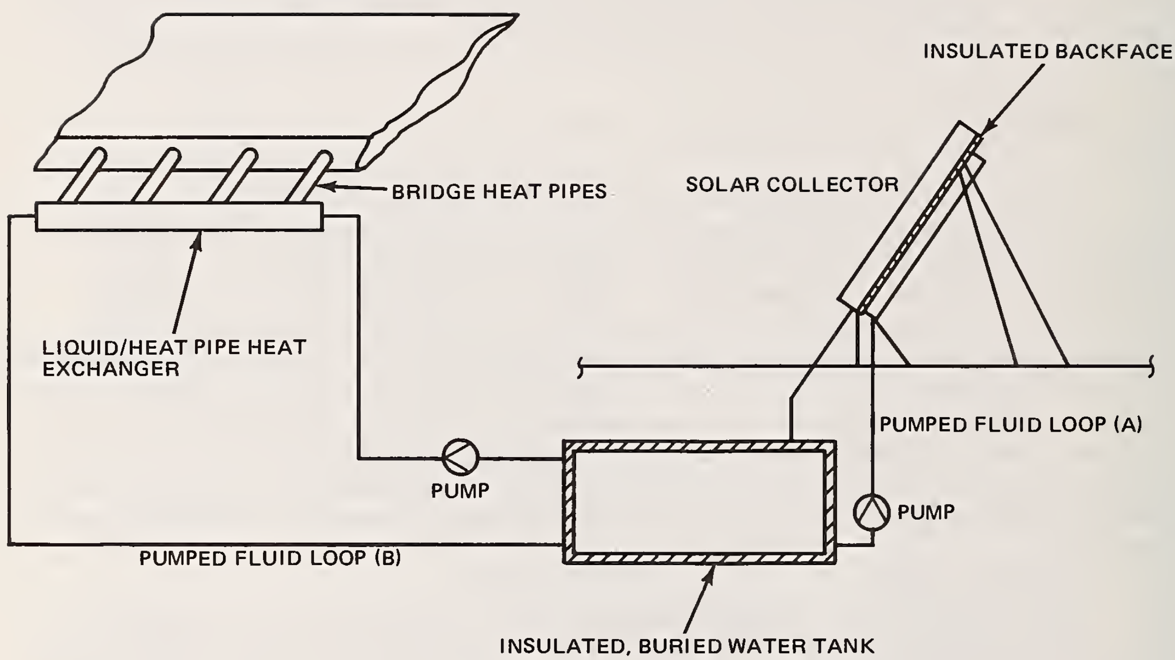


Figure 81 Schematic of solar collector/heat pipe design to prevent icing on highway bridge decks

- Frequency of icing

- Amount of solar energy available.

The energy dissipated per event on an annual basis was already determined for each of the sites from analytical results and recorded weather data. January weather data recorded over the past several years was reviewed to establish the average frequency and length of preferential icing events. Tables 17 and 18, based on this review, were prepared for New York City and Oklahoma City, respectively. These tables summarize the intervals between icing events and the length of each event for the past ten Januarys for New York City and for the past seven Januarys for Oklahoma City. The interpretation of these weather data, of course, involves considerable engineering judgement; on this basis, an average icing event of 1.57 days and an interval between events of 3.25 days was estimated for New York and 1.9 days per event and 4.8 days between events was estimated for Oklahoma City.

Since prolonged cloud and fog conditions that exist in Fresno during December and January limit the available solar energy, that site was not considered in this initial study.

2.9.2 Solar Collector Performance

The amount of solar energy incident on a flat plate collector depends on the tilt angle of the assembly. For a 40 degree north latitude, such as New York City, the maximum energy would be incident during the winter months for a panel tilted about 55 degrees towards the equator. For conservatism, the analysis was based on the less optimum tilt of 40 degrees. Oklahoma City, which is at a latitude of 36 degrees, was also studied for a 40 degree collector angle.

Reference 4 presents the monthly mean daily solar energy incident on a horizontal surface, as recorded over a 30 year period for various sites throughout the United States. Based on this information, the mean daily solar energy incident on a horizontal surface in January for New York City was calculated as 1.5 kwh/m^2-day (44 Btu/ft^2-day). With the 2.6 factor calculated for the ratio of energy incident on a surface tilted 40 degrees towards the equator to that incident on a horizontal surface (also see Appendix B and Reference 7), the mean daily solar energy incident on such a surface was calculated at 3.9 kwh/m^2-day (1,240 Btu/ft^2-day) for January, or 121 kwh/m^2 (38,450 Btu/ft^2) for the entire month. Similarly, a surface tilted 40 degrees to the equator in Oklahoma City would have an average daily solar flux of 7.3 kwh/m^2-day (2340 Btu/ft^2-day) and a monthly total of 234 kwh/m^2 (74,394 Btu/ft^2).

The efficiency of the collector in absorbing energy depends primarily on the plate and ambient temperatures, incident energy, sky temperature (effective radiative sink temperature), and wind speed. Figure 82 parametrically describes the variation of efficiency for Grumman's Model 50 collector as a

Table 17 Frequency of Preferential Bridge Icing
for New York City During January

Year	No. of No-Icing Days/No. of Icing Days Sequence
1965	7/1/4/2/4/5/2/2/1/2/1
1966	0/1/3/1/1/1/11/1/8/2/1/1
1967	0/1/1/2/1/2/1/14/2/7/3/2/1/3
1968	0/1/1/1/2/2/1/1/12/1/2/1/3/1/2
1969	2/2/1/3/3/1/4/2/1/2/1/1/1/3/4
1970	0/1/2/2/7/2/2/1/5/5/1/2/1
1971	4/1/3/1/4/2/4/1/4/1/1/2/3
1972	2/1/16/1/1/1/6/1/2
1973	0/1/1/2/1/1/2/4/5/2/1/1/4/1/5
1974	0/1/1/1/2/1/1/1/4/2/3/1/1/1/10/1
	Average icing event = 1.57 days Average period between icing events = 3.25 days

Table 18 Frequency of Preferential Bridge Icing
for Oklahoma City During January

Year	No. of No-Icing Days/No. of Icing Days Sequence
1968	1/5/1/4/11/1/5/2/1
1969	9/1/7/1/3/1/3/1/1/2/1/1
1970	4/1/4/1/5/6/10
1971	2/2/7/2/4/1/4/1/8
1972	0/1/1/2/9/1/6/1/4/3/2/1
1973	1/2/1/6/14/1/1/2/3
1974	0/2/9/1/15/1/3
	Average icing event = 1.9 days Average period between icing events = 4.8 days

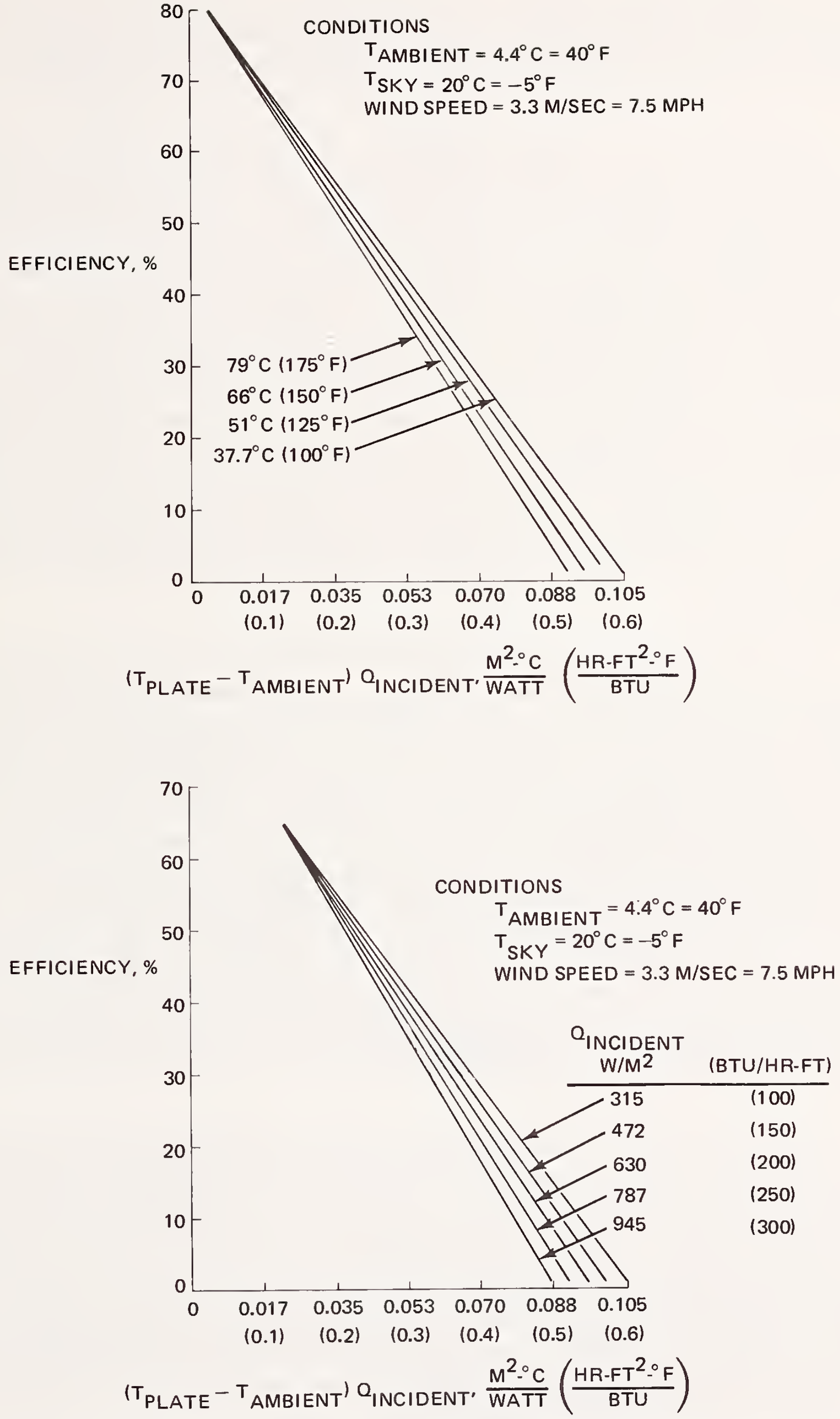


Figure 82 Typical solar collector efficiency (Grumman Sunstream Model 50 Solar Collector)

function of these parameters. For purposes of this preliminary evaluation, an average solar collector efficiency of 50 percent was assumed reasonable; therefore, of the 121 kwh/m^2 (38,450 Btu/ft^2) incident on the tilted solar collector in New York City, 60.5 kwh/m^2 (19,225 Btu/ft^2) would be absorbed.

A portion of the absorbed energy is lost due to conduction from the tank as well as line losses. The temperature of the bridge heat pipes and absorber panel is directly related to the tank temperature. In Grumman's solar collector design, panel temperature will be no more than 5.56°C (10°F) hotter than the tank temperature. As shown in figure 82, as the collector (absorber) gets warmer, the efficiency gets lower. A fairly low collector (and hence tank) temperature thus is preferred. Another reason for avoiding high tank temperatures is to keep the deck heat pipe temperature from inducing severe thermal stresses in the concrete. Maintenance of tank temperature at, or below, 26.7°C (80°F) thus is recommended. Conduction losses from the buried water tank to the surrounding soil are accounted for by conservatively assuming that the tank temperature remains at 26.7°C (80°F) throughout the month, and the soil at 4.4°C (40°F). The tank also is assumed to be surrounded with 30.48 cm (1 ft) of ureathane insulation. Figure 83 presents the results of this analysis, and gives the average monthly heat loss from the tank as a function of tank capacity.

In order to determine required tank capacity, the total energy to be removed from the tank and the acceptable temperature drop must be known. A review of the weather data indicated that the tank should provide energy for up to three icing events, in both New York City and Oklahoma City; that is, under extreme conditions there would be little solar energy collected by the system for an interval spanning up to three icing events. Thus, since each icing event requires about 0.378 kwh/m^2 (120 Btu/ft^2) and 0.68 kwh/m^2 (216 Btu/ft^2) of deck surface for New York City and Oklahoma City, respectively, the tank would have to be capable of supplying about 1.1 kwh/m^3 (360 Btu/ft^2) and 2 kwh/m^2 (648 Btu/ft^2) of deck for New York City and Oklahoma City, respectively. If the tank temperature were allowed to drop by 5.56°C (10°F) while providing this energy, 179.26 and 317.56 litres of water would be required per square meter of bridge deck for New York City and Oklahoma City, respectively. A temperature drop of 11.1°C (20°F) would naturally halve these requirements to 89.63 and 158.78 litres/m^2.

Figures 84 and 85 summarize the solar collector area and tank size required to provide the energy needed to avoid preferential bridge icing in New York City and Oklahoma City. As shown in the figures, the allowable temperature drop of the tank has a large effect on the tank size, but little effect on the solar collector area required. For example, decreasing the allowable temperature drop of the tank from 11.1 to 5.56°C (20 to 10°F) would require an increase in tank size from about 166,540 to 333,080 litres (44,000 to 88,000 gallons), but would only require a solar collector area increase from about 122 m^2 to 126 m^2 (1320 to 1360 ft^2) for a 1858 m^2 (20,000 ft^2) bridge in New York City.

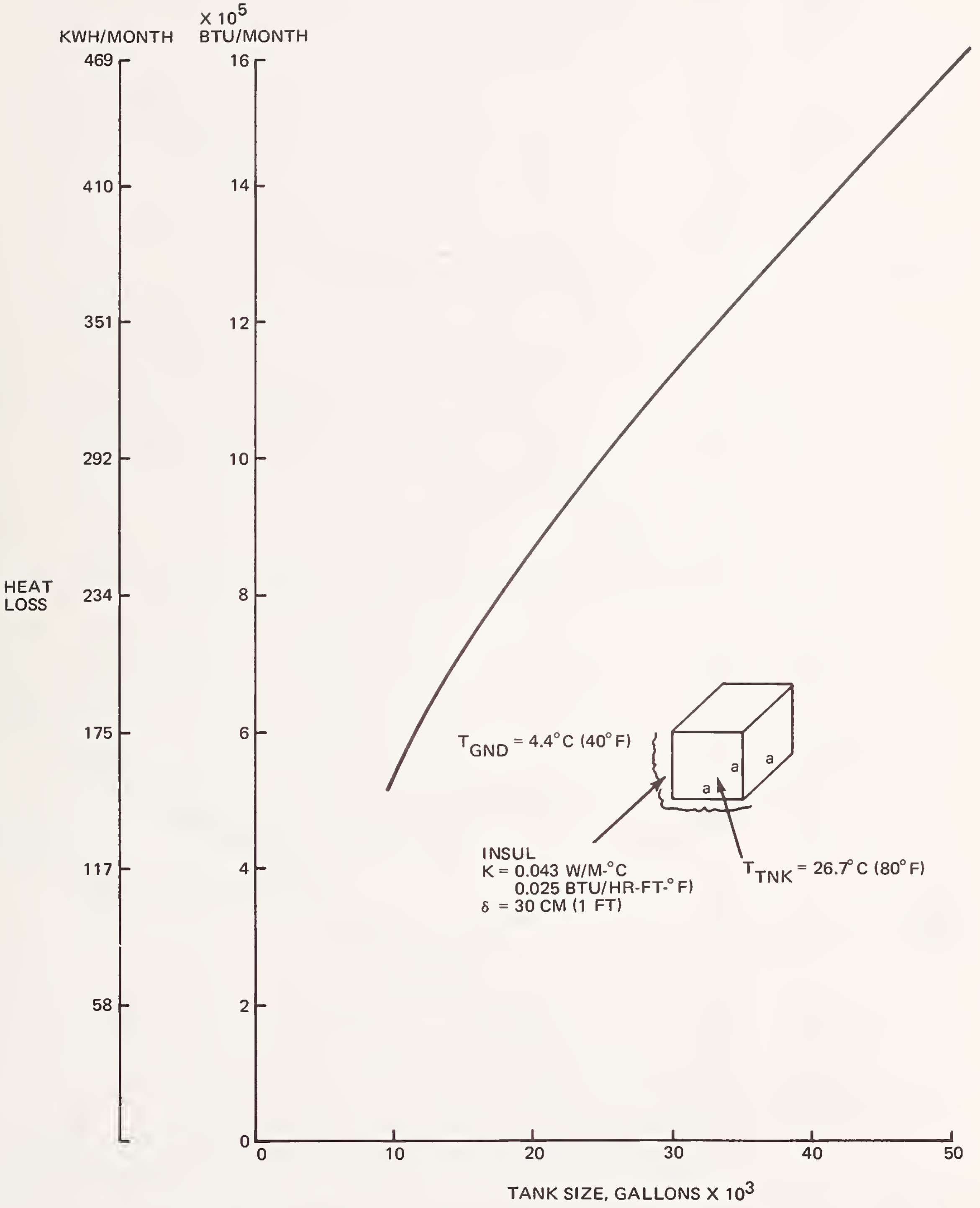


Figure 83 Monthly heat loss from buried water tank

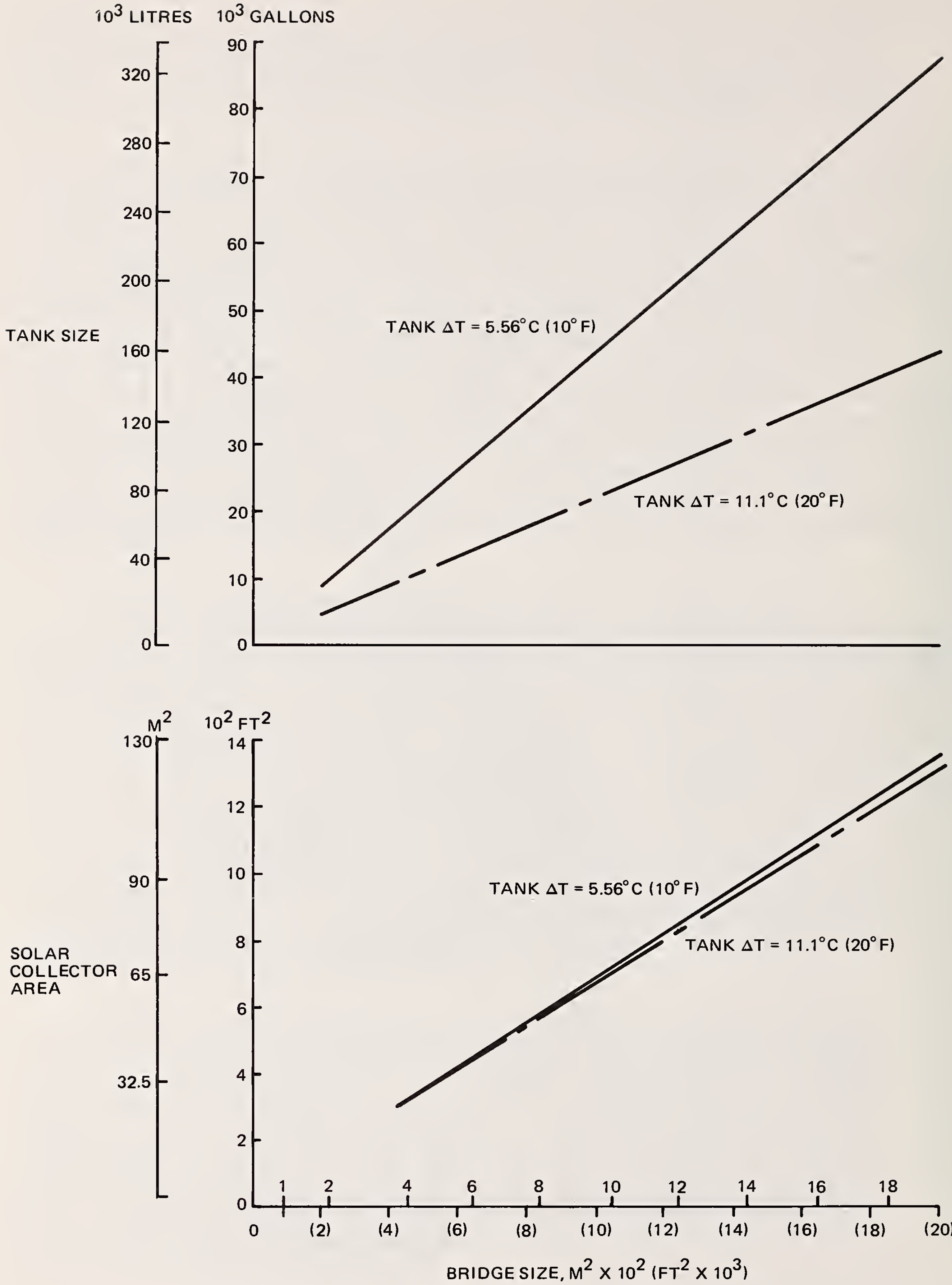


Figure 84 Solar collector design requirements for New York City

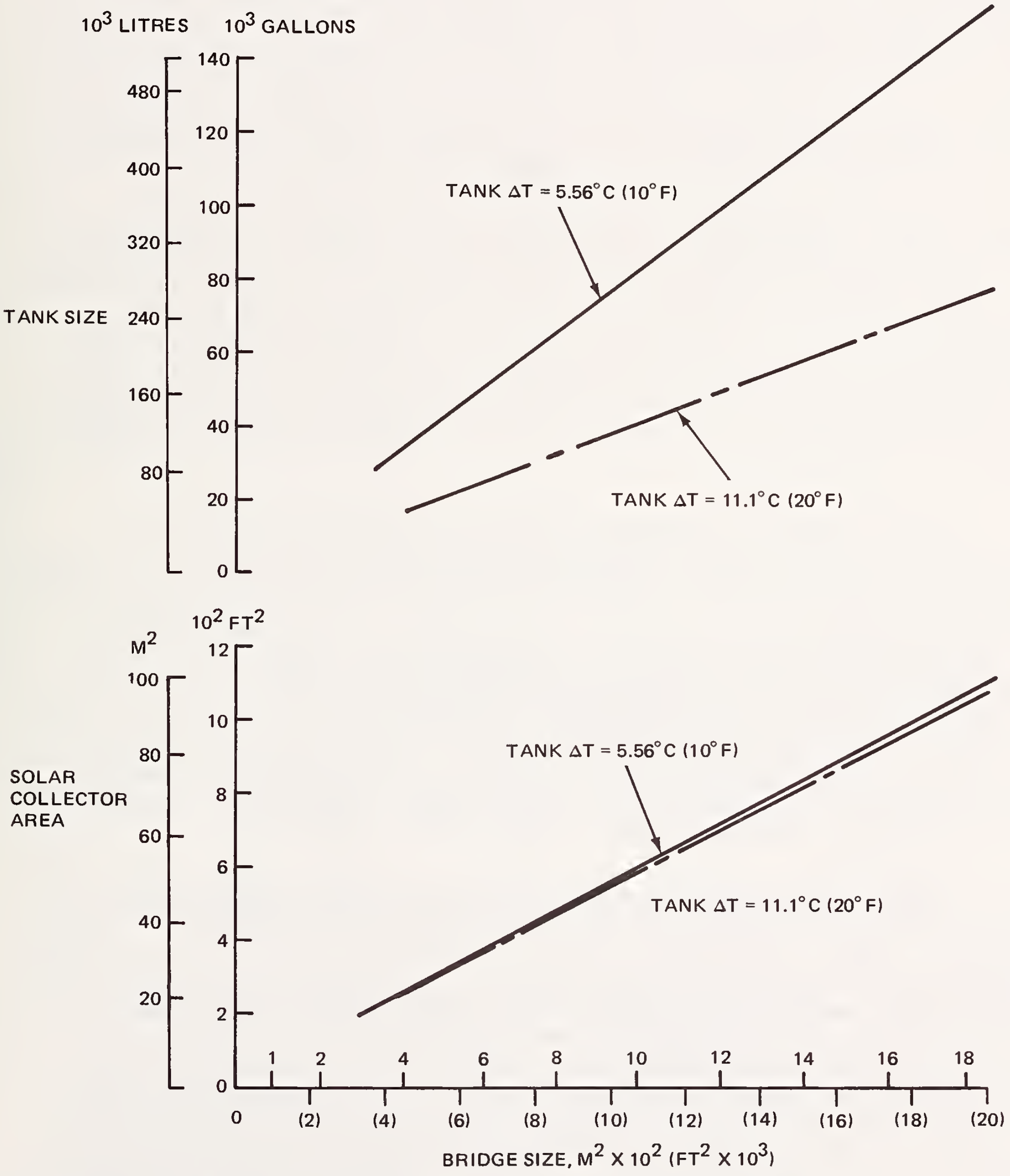


Figure 85 Solar collector design requirements for Oklahoma City

2.10 ECONOMIC EVALUATION OF SOLAR COLLECTOR AND EARTH HEAT PIPE SYSTEMS

The preliminary design information that has been obtained provides a means for evaluating and comparing the feasibility of the solar collector and earth heat pipe systems. Tables 19 and 20 present solar collector system cost breakdowns for a 465 m^2 (5000 ft^2) and 1858 m^2 (20,000 ft^2) bridge in New York City and Oklahoma City, respectively. As shown in the tables, the bridge heat pipes represent a significant percent of the total cost. With the bridge heat pipes on 2.29 cm (9 inch) centers, a solar collector/heat pipe system for New York City, table 19, would cost about \$172/m^2 (\$16/ft^2) for a 465 m^2 (5000 ft^2) bridge and \$133/m^2 (\$12.39/ft^2) for a 1858 m^2 (20,000 ft^2) bridge. The lower cost with increasing bridge size is due primarily to the relatively lower cost of larger capacity tanks, figure 86, and to the assumption that assembly costs do not increase proportionately with bridge size. Moreover, since the solar collector design yields a higher temperature source than the earth source design, the bridge heat pipes can probably be spaced further apart than on 22.9 cm (9 inch) centers. A cost estimate has thus been prepared for bridge heat pipes on 45.7 cm (18 inch) centers. This change provides a considerable savings: system cost is reduced to \$136/m^2 (\$12.66 ft^2) for a 465 m^2 (5000 ft^2) bridge and to \$97/m^2 (\$9.05/ft^2) for a 1858 m^2 (20,000 ft^2) bridge. The allowable spacing of the bridge heat pipes should thus be more thoroughly examined in further efforts.

As shown in table 20, a similar analysis for Oklahoma City yields an estimated system cost of \$193 and \$144 per square metre (\$17.94 and \$13.36 per square foot) of deck surface for 465 and 1858 m^2 (5000 and 20,000 ft^2) bridges with heat pipes on 22.9 cm (9 inch) centers. Increasing this bridge heat pipe spacing to 45.7 cm (18 inch) centers lowers this system cost to \$157 and \$107 per square metre (\$14.59 and \$10.02 per square foot) of deck for the 465 and 1858 m^2 (5000 and 20,000 ft^2) bridges. These costs correlate with those presented in tables 19 and 20, which also indicate that system costs are slighly higher for Oklahoma City than for New York City, due to the need for a larger capacity tank in the former location. Based on energy estimates, 317.94 liters/m^2 (7.8 gallons/ft^2) of bridge surface is required in Oklahoma City compared to 179.03 litres/m^2 (4.4 gallons/ft^2) for New York.

As shown in table 16, an earth heat pipe system costs \$219 and \$303 per metre (\$20.41 and \$17.85 per square foot) for 465 and 1858 m^2 (5000 and 20,000 ft^2) bridges, respectively. The main difference between these systems is obviously the method of providing energy to the bridge: one uses a solar collector/water tank system and the other an earth heat/heat pipe system. Table 21 compares these systems on the basis of energy source. As shown in the table, the solar collector system is considerably less expensive than the earth heat pipe system for both New York City and Oklahoma City. And, since the solar collector/tank cost does not increase proportionally with area, but the earth heat pipe system does, the savings increases with increasing bridge size. In addition, the solar collector design may yield an even greater saving since the spacing between the bridge heat pipes can be increased; that saving has not even been taken into account in preparing the table.

Table 19 Estimated Costs of Solar Collector Heat Pipe System for New York City

Item	Cost									
	465 m^2 (5000 Ft^2)**					1858 m^2 (20,000 ft^2)**				
				% of Total*					% of Total*	
Item	Total $	$\$/m^2$	$\$/ft^2$	A	B	Total $	$\$/m^2$	$\$/ft^2$	A	B
Tank**	17,600	37.90	3.52	22	28	49,280	26.48	2.46	20	27
Solar Collector	3,960	8.50	0.79	5	6	14,916	8.07	0.75	6	8
Heat Pipes****										
22.9 cm (9 in.) Centers	33,500	72.12	6.70	42	—	133,500	71.90	6.68	59	—
45.7 cm (18 in.) Centers	16,750	36.00	3.35	—	27	66,750	35.95	3.34	—	37
Assembly	25,000	53.82	5.00	31	39	50,000	26.91	2.50	20	28
Total										
22.9 cm (9 in.) Centers	80,060	172.33	16.01	100	—	247,696	133.37	12.39	100	—
45.7 cm (18 in.) Centers	63,310	136.27	12.66	—	100	180,946	97.42	9.05	—	100

*"A" represents system with heat pipes on 22.9 cm (9 inch) centers; "B" represents system with heat pipes on 45.7 cm (18 inch) centers.

**465 m^2 (5000 ft^2) bridge is 15.24 m (50 ft) wide and 30.48 m (100 ft) long; 1858 m^2 (20,000 ft^2) bridge is 15.24 m (50 ft) wide and 121.9 m (400 ft) long.

***Tank cost obtained from figure 86.

****Heat pipes are 15.24 m (50 ft) long.

Table 20 Estimated Costs of Solar Collector Heat Pipe System for Oklahoma City

Item	Cost									
	465 m^2 (5000 ft^2) **					1858 m^2 (20,000 ft^2) **				
				% of Total*					% of Total*	
Item	Total $	$\$/m^2$	$\$/ft^2$	A	B	Total $	$\$/m^2$	$\$/ft^2$	A	B
Tank**	27,936	60.17	5.59	31	38	71,392	38.43	3.57	27	36
Solar Collector	3,245	6.99	0.65	4	4	12,232	6.57	0.61	5	6
Heat Pipes****										
22.9 cm (9 in.) Centers	33,500	72.12	6.70	37	—	133,500	71.90	6.68	50	—
45.7 cm (18 in.) Centers	16,750	36.06	3.35	—	23	66,750	35.95	3.34	—	33
Assembly	25,000	53.82	5.00	28	34	50,000	26.91	2.50	19	25
Total										
22.9 cm (9 in.) Centers	89,681	193.11	17.44	100	—	267,124	143.81	13.36	100	—
45.7 cm (18 in.) Centers	72,931	157.05	14.59	—	100	200,374	107.85	10.02	—	100

*"A" represents system with heat pipes on 22.9 cm (9 inch) centers; "B" represents system with heat pipes on 45.7 cm (18 inch) centers.

**465 m^2 (5000 ft^2) bridge is 15.24 m (50 ft) wide and 30.48 m (100 ft) long; 1858 m^2 (20,000 ft^2) bridge is 15.24 m (50 ft) wide and 121.9 m (400 ft) long.

***Tank cost obtained from figure 86.

****Heat pipes are 15.24 m (50 ft) long.

Table 21 Comparison of Costs of Solar Collector and Earth Heat Pipe Energy Sources for New York City and Oklahoma City

System	Cost					
	465 M^2 (5000 Ft^2)			1858 M^2 (20,000 Ft^2)		
	Total $	$/$M^2$	$/$Ft^2$	Total $	$/$M^2$	$/$Ft^2$
Solar Collector New York City	21,560	46.39	4.31	64,196	34.55	3.21
Solar Collector Oklahoma City	31,181	67.16	6.24	83,624	44.99	4.18
Earth Heat Pipe*	43,550	93.75	8.71	173,500	93.32	8.67

*Earth heat pipe system costs are the same for New York City and Oklahoma City

Note: Operating costs for solar & earth HP systems are minimal

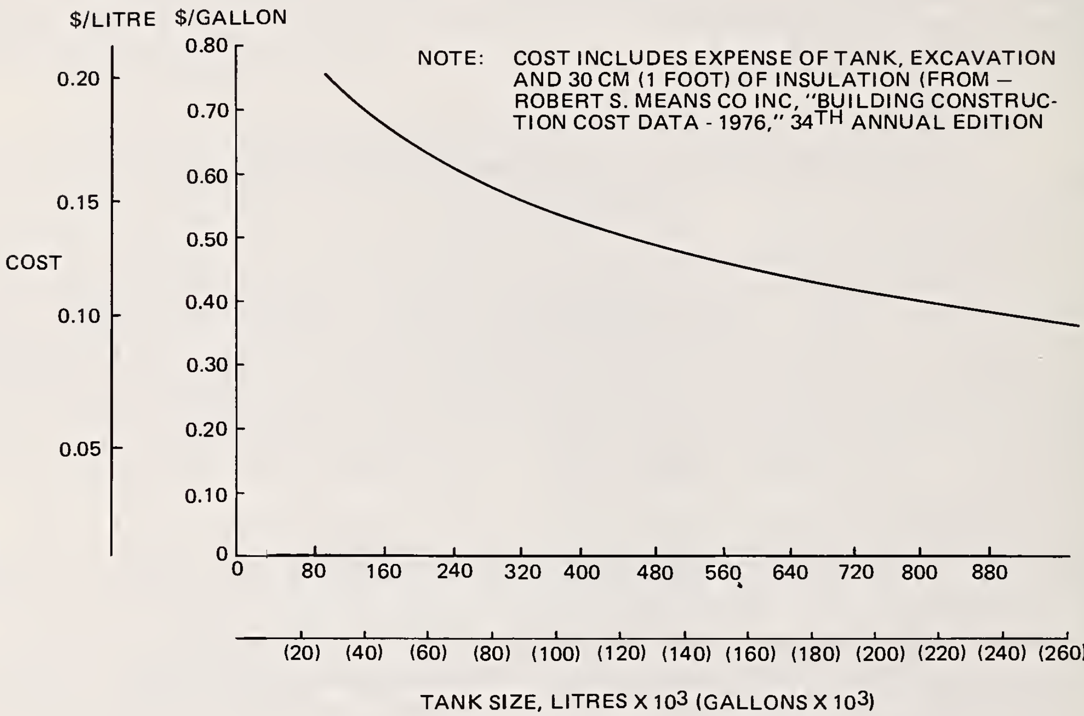


Figure 86 Variation of buried water tank cost with size

On the basis of this analysis, a solar collector/heat pipe system with heat pipes on 22.9 cm (9 inch) centers will cost about $\$172/m^2$ ($\$16/ft^2$) and $\$194/m^2$ ($\$18/ft^2$) to avoid preferential icing on 465 m^2 (5000 ft^2) bridges in New York City and Oklahoma City. System costs will decrease to about $\$140/m^2$ ($\$13/ft^2$) as bridge size increases to 1858 m^2 (20,000 ft^2). By comparison, an earth heat pipe system costs about $\$215/m^2$ ($\$20/ft^2$) and $\$193/m^2$ ($\$18/ft^2$) for 465 and 1858 m^2 (5000 and 20,000 ft^2) bridges in both locations. Although these values present only a first estimate, they do suggest that a solar collector design may offer significant advantages, and therefore would warrant further consideration.

Section 3

CONCLUSIONS/RECOMMENDATIONS

By using the natural energy available in the earth, a heat pipe system can prevent the preferential freezing of highway bridge decks. However, since the earth represents a low-grade energy source, ranging from 7.2 to 15.6°C (45 to 60°F), system temperature drops must be minimized for the design to function. Since testing indicated a large temperature drop across the mechanical joints between heat pipes, the earth and bridge heat pipes should be coupled via a pumped fluid loop.

Although performance is adequate with this basic design, system cost would be improved if a more efficient energy source were used. For example, the low earth temperature limits the allowable spacing between bridge heat pipes to 15 to 23 cm (6 to 9 inch) centers. If a higher temperature source were used this spacing could be increased, with an attendant decrease in the number of pipes required and, hence, system costs. Therefore, use of either an additional energy source or some method of augmenting earth heat should be considered.

As an example, a preliminary evaluation of a solar collector/heat pipe design indicated that system costs would be decreased if such an approach were implemented. Whereas costs were estimated at about \$215/m^2 (\$20/ft^2) for the earth heat pipe system, a solar collector design would be in the \$100/m^2 (\$10/ft^2) to \$194/m^2 (\$18/ft^2) range. Since costs must be lowered before preferential de-icing systems are likely to be widely applied, the solar collector design and other energy alternatives should be explored more fully.

APPENDIX A

DESIGN MANUAL FOR HIGHWAY ENGINEERS

A heat pipe system has been developed to use the natural energy available in the earth to prevent preferential freezing of highway bridge decks. The system uses temperature sensors, and moisture sensors in some locations, to activate a pumped loop system which connects heat pipes inserted into the ground with heat pipes inserted in the deck slab, figure A-1. This system functions properly in areas where it is economically feasible to prevent preferential icing (areas with fewer than 150 days of below-freezing temperatures, figure 88), if a metre of 2 inch, nominal, earth heat pipe is provided for each 0.3 square metre of bridge deck, with 1/2 inch, nominal bridge heat pipes on 23 cm centers (or a foot of earth heat pipe is provided for each square foot of bridge deck, with the bridge heat pipes on 9 inch centers). The volume of earth required naturally depends on location.

The bridge and earth heat pipes must be fabricated with integral heat exchanger sections built into one end so that they can be connected to each other through a pumped loop system. The fluid loop is included to minimize the overall temperature drop from the soil to the deck slab. This appendix presents the specific requirements of each element of the design.

A.1 BRIDGE HEAT PIPES

Bridge heat pipes should be constructed of 1/2 inch, nominal, Schedule 40 carbon steel pipe, and charged with anhydrous ammonia working fluid. The heat pipes should be spaced along the bridge length on 23.9 cm (9 inch) centers at the mid-plane of the bridge slab, and must be sloped so that the ends of the pipe at the center of the bridge are at least 5 cm (2 inches) higher than the ends of the pipe at the side of the bridge. This slope allows gravity to assist in the return of the working fluid. The outside end of the pipe is to be butt welded to a shell and tube heat exchanger section, figure A-2.

A.2 EARTH HEAT PIPES

Earth heat pipes should be constructed of 2 inch, nominal, Schedule 40 carbon steel pipe, and charged with anhydrous ammonia working fluid. One metre of heat pipe should be provided for each 0.3 square metre of bridge deck (or 1 foot of pipe for each square foot of bridge deck). To simplify pumped loop connections, the upper end of the heat pipe should be butt welded to a heat exchanger. The holes for the pipe should be drilled by the method most suitable for the specific location. The holes should then be backfilled, and the top ends of the pipes bent over until the heat exchanger is about 5 degrees from horizontal. In order to enable the heat exchanger and run-around loop

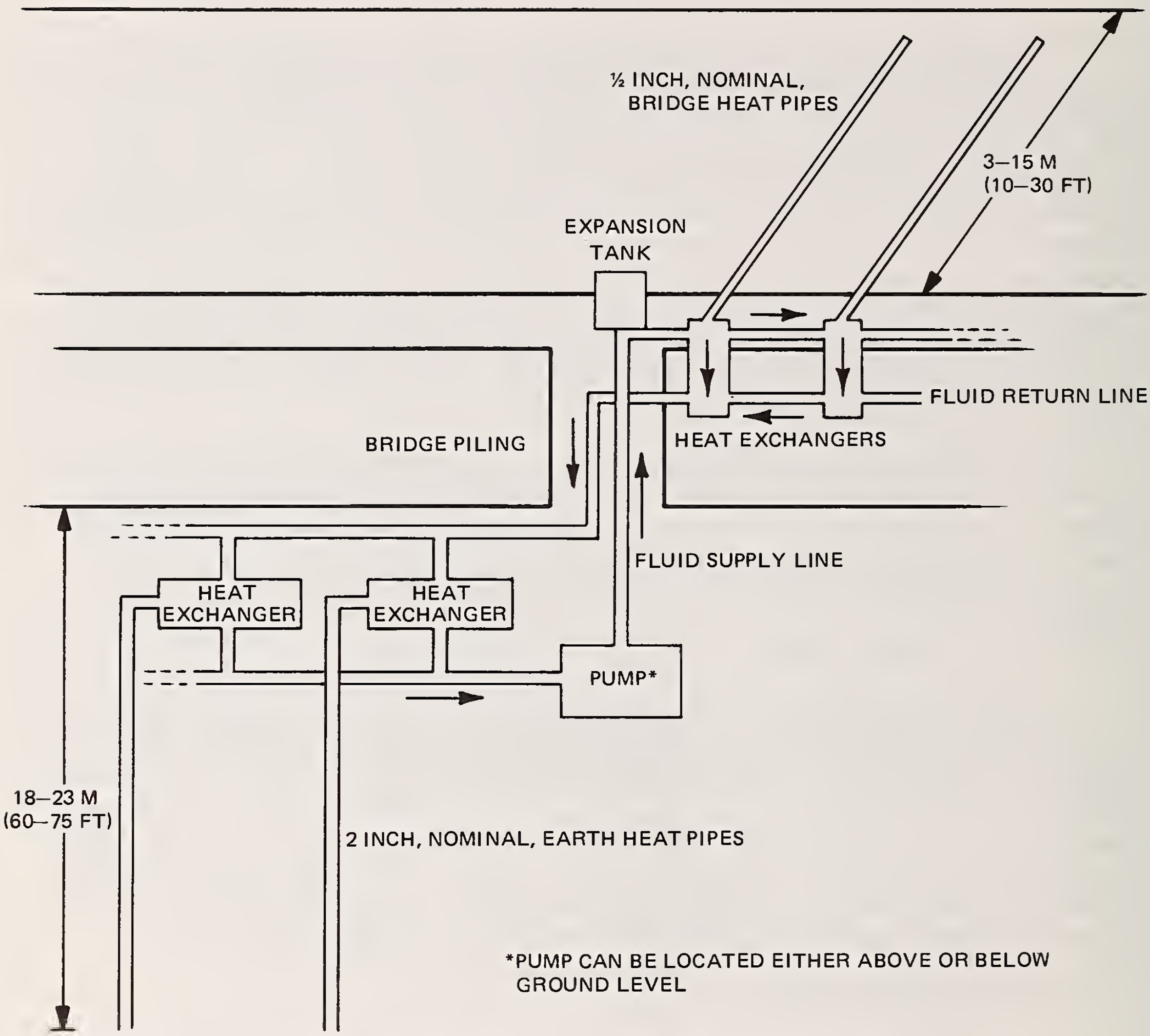


Figure A-1 Earth heat pipe preferential bridge de-icing system

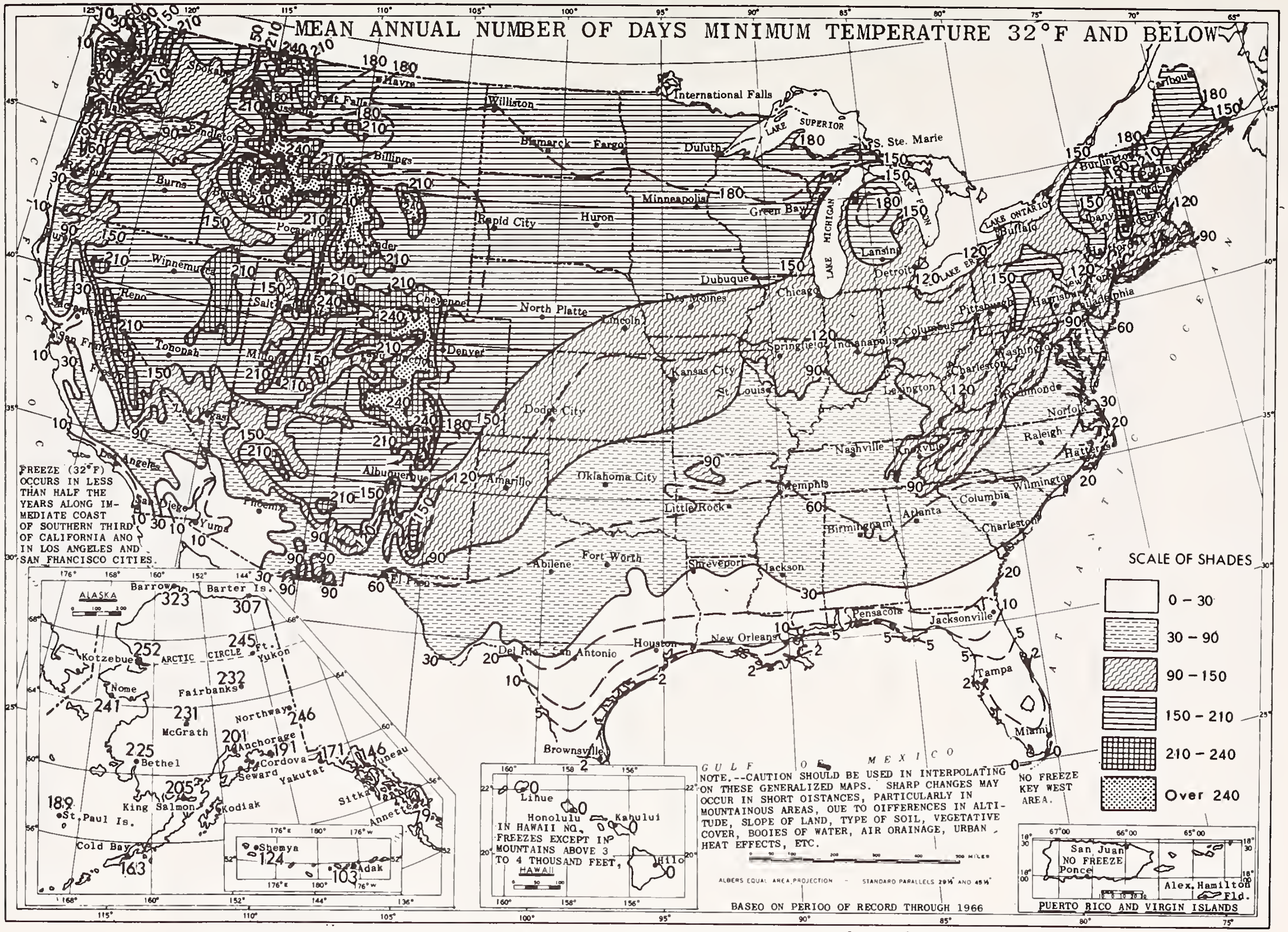


Figure A-2 Mean annual number of days of minimum temperatures of O°C (32°F) and below

piping to be placed below ground, the holes for the heat pipes should be drilled from the bottom of a trench that is dug to a depth of about 1 metre (3 feet).

A.3 HEAT EXCHANGER DESIGN

The total temperature drop introduced into the system by the heat exchangers should be about 2 to 3°C (5 to 6°F). The total pressure drop through both heat exchangers (bridge heat pipe and earth heat pipe) should not exceed 0.148 kg/cm (2 psi) or 140.82 cm (4.62 ft) of water. The heat exchanger should be of the shell and tube type shown in figure A-3.

The ΔT for a given heat exchanger can be determined by first calculating:

$$\epsilon_{H/X} = 1 - 1/e^{Ntu}$$

where $\epsilon_{H/X}$ = Heat exchanger efficiency

Ntu = No. of transfer units = $UA/\dot{m}c_p$

UA = Overall heat transfer coefficient of heat exchanger

$\dot{m}$ = Mass flow rate of liquid

c_p = Liquid specific heat

The fluid temperature change through the heat exchanger can then be determined:

$$\Delta T_f = \dot{Q}/\dot{m}c_p$$

where $\dot{Q}$ = heat transfered during cycle

The temperature of the fluid, as it passes through the heat exchangers, is shown schematically in figure A-3.

The following equations can be used to determine the difference in temperature between the earth and bridge heat pipes:

$$\Delta T_1 = (T_{\text{earth pipe}} - T_{\text{fluid min}}) = \Delta T_f/\epsilon_{H/X \text{ earth pipe}}$$

$$T_{\text{fluid max}} = \Delta T_f + T_{\text{earth pipe}} - \Delta T_1$$

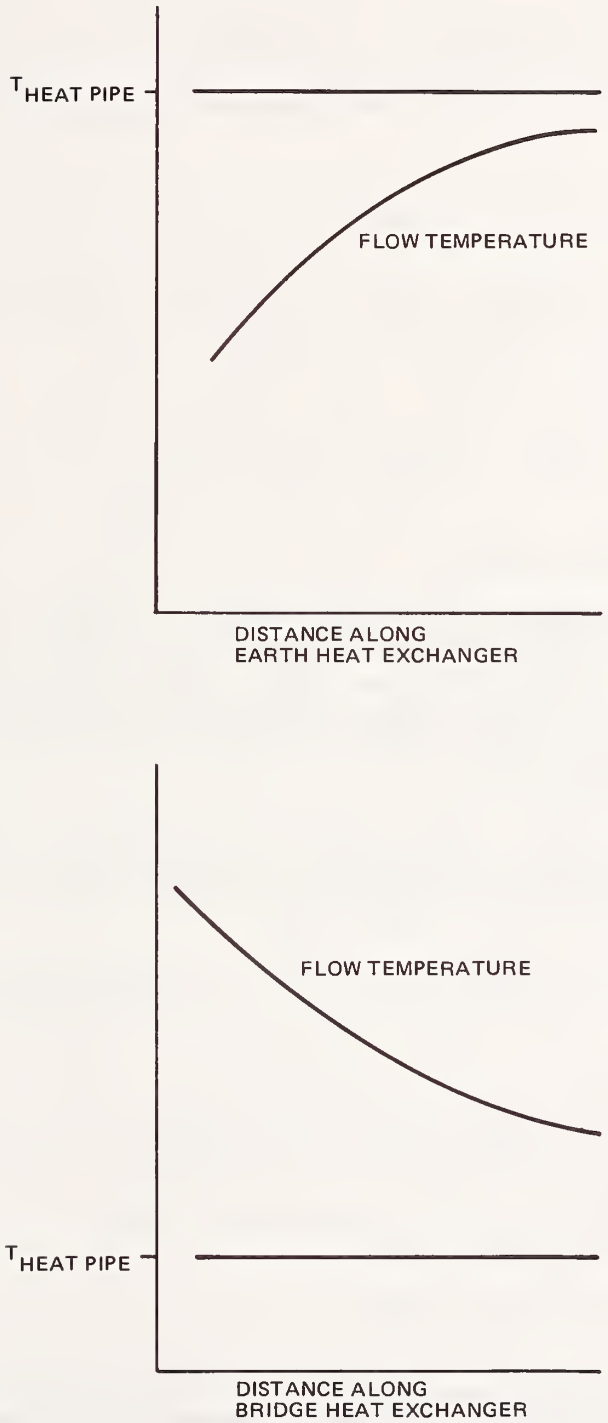


Figure A-3 Run around loop flow temperatures in heat exchangers

$$T_{\text{bridge pipe}} = T_{\text{fluid max}} - T_f/\epsilon_{H/X \text{ earth pipe}}$$

$$\Delta T_{\text{total}} = T_{\text{earth pipe}} - T_{\text{bridge pipe}}.$$

As an example, for a 10°C earth pipe with $\epsilon_{H/X} = 50\%$ and $\Delta T_f = \dot{Q}/\dot{m}c_p = 1.1°C$,

$$\Delta T_1 = 1.1°C/0.50 = 2.22°C$$

$$T_{\text{fluid max}} = 10°C + 1.11°C - 2.22°C = 8.89°C$$

$$T_{\text{bridge pipe}} = 8.89°C - 1.1°C/50\% = 6.69°C$$

$$\Delta T_{\text{total}} = 10°C = 6.69°C + 3.31°C$$

A.4 HEADER FLOW SYSTEM

The heat exchangers should be connected in parallel, as shown in figure A-4, with the pipe sized so that it can handle the total flow with small pressure drop. Mechanical fittings, such as the Aeroquip 6-B groove pipe coupling, should be provided on heat exchanger and header pipes to make connection in the field easier. Pressure drops for steel pipe may be determined from figure 90.

The pipe sections exposed to the air must be covered with insulation; many commercial types are available. The rate of loss per length of pipe length can be determined from the formula

$$Q \text{ per length} = \frac{2\pi K \ell}{\ell n\ (R_o/R_i)} (T_{air} - T_{pipe}) (2\pi K \ell)/\ell n\ (R_0 - R_i)$$

where

K = thermal conductivity of the insulation

ℓ = length

R_o = Insulation outer radius

R_i = Insulation inner radius

The total system Q loss should be limited to the output of one earth pipe: about 0.95 kw (3250 Btu/hr). Figure 77 presents typical insulation heat loss for various pipe sites and insulation thicknesses.

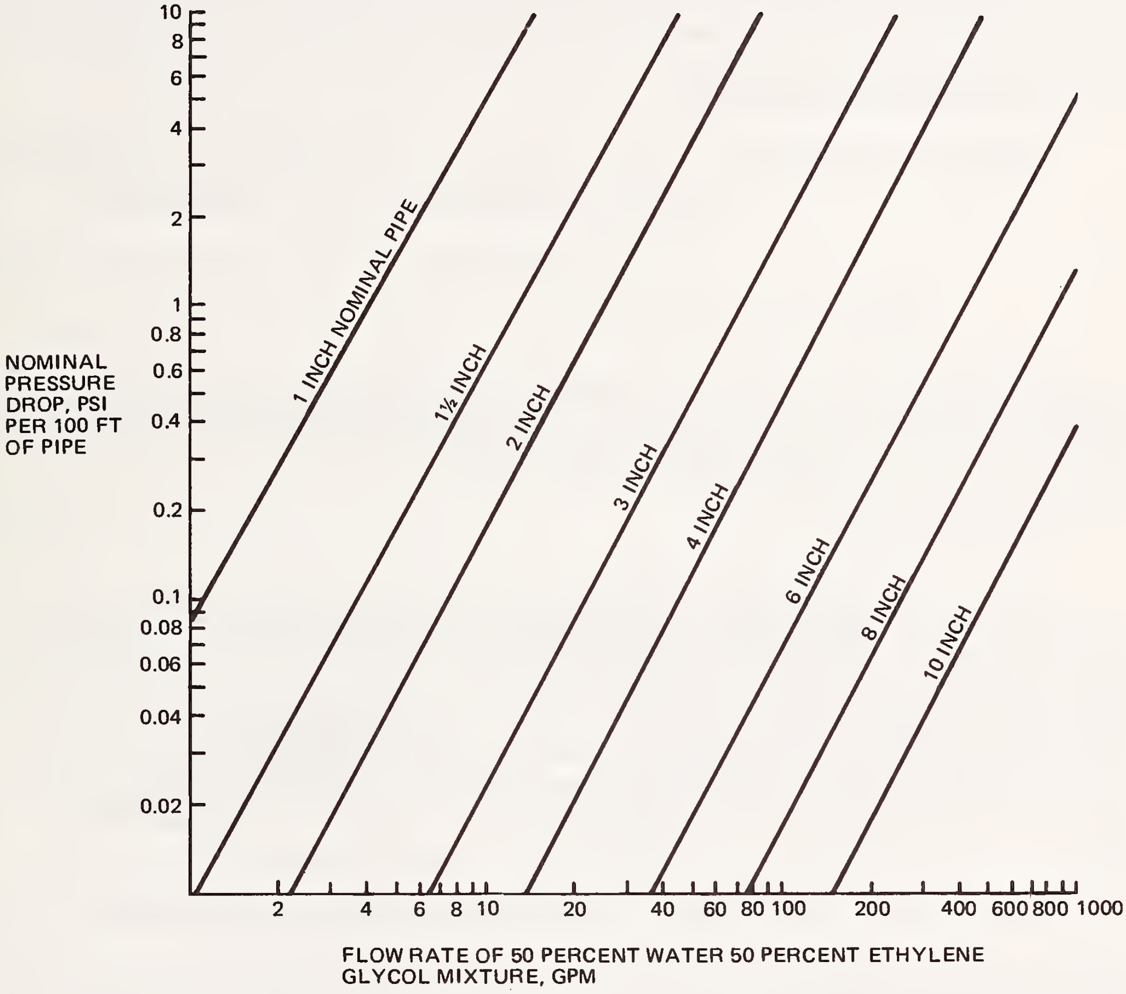


Figure A-4 Pressure drop for flow in nominal steel pipe

A.5 PUMPS

The pump used for flow circulation must be capable of providing the required flow at the resulting pressure drop. A centrifugal type pump is most suitable to these high volume flow applications; a commercially available unit can be selected after the total system pressure drop and fluid flow requirements are established.

A.6 EXPANSION TANK

An expansion tank is needed in order to allow for increased liquid volume during heating. Since the circulating liquid, such as NuTek 800 (water-glycol), is never near its atmospheric boiling temperature, an ambient pressure tank may be used. The tank must be large enough to allow for the greatest possible size increase:

$$\text{Minimum Tank Volume} = \text{total liquid volume (coefficient of expansion)} \Delta T_{max}$$
$$= (\text{volume of water at } T_{max} - \text{volume of water at } T_{min})$$

Additional volume will reduce the frequency at which the system must be refilled. Since the expansion tank is an ambient pressure vessel, it must be located at the top of the system (at bridge level).

A.7 SYSTEM SIZING

Since preferential icing conditions (temperature, water presence, etc) are the same for any location, the rate at which energy must be provided is also the same. As a result, system parameters which affect this energy rate, such as spacing of bridge pipes and the number of earth pipes required for a given size bridge surface, are also the same. If the recommended 1 meter of earth pipe length is used for each 0.3 square metre of bridge surface, the number of earth pipes can be determined simply by dividing the bridge surface area by the pipe length. For example, for a 19.8 meter (65 foot) earth heat pipe:

$$\text{No. of 19.8 m earth pipes} = m^2 \text{ of Bridge Surface Area}/19.8 \text{ m } (0.3 \text{ m})$$

If earth pipes of a different length are used, that length should be substituted for the 19.8 in the formula.

For crowned roadways, the number of bridge pipes is determined by dividing the total length of the bridge by the 22.9 cm (9 inch) pipe spacing and multiplying by two, since the pipes are installed from both sides of the bridge:

$$\text{No. of bridge pipes} = 2 \text{ (m of bridge length)}/0.229 \text{ m}$$

The size of the earth heat pipe field must be determined for each location from its total annual energy requirement. Since the earth field should not be permitted to drop more than 2.78°C (5°F) in average temperature over a winter season, the required soil volume should be

Soil Volume = Required Annual Energy/(Soil Density) (Soil Specific Heat) (2.78°C)

The annual energy demand for a given location can be estimated by multiplying the number of days in the year that the minimum temperature falls below 0°C (32°F) by 0.252 kwh/m^2 (80 Btu/ft^2) of bridge. Figure 89 is chart that shows the number of below 0°C (32°F) days per year for locations within the United States.

The surface area of the heat pipe field is determined by dividing its volume by the heat pipe depth:

Surface Area = Soil Volume/Heat Pipe Depth

The spacing of the earth heat pipes is then:

$$\text{Spacing of Earth Heat Pipes} = \sqrt{\text{Surface Area/No. of Pipes}}$$

As an example, the soil volume required for a 465 m^2 bridge in Washington, D.C. would be determined as follows:

No. of 19.8 m earth heat pipes = 465/(19.8) (0.3048) = 77

No. of Days with T <0°C $\cong$ 80

Annual Energy Requirement = (80) (0.252) = 20 kwh/m^2
= 9300 kwh for whole deck

$$\text{Soil Volume} = 9300\ \text{kwh}/\left[(9300\ \text{kg/m}^3)\ (0.23\ \text{w-hr}/1000/\text{kg-°C})\ (2.78°\text{C})\right] = 11363\ \text{m}^3$$

Surface Area = 11,363 m^3/19.8 m = 573.9 m^2

$$\text{Spacing of Earth Heat Pipes} = \sqrt{573.9/77} = 2.7\ \text{m}$$

APPENDIX B

ANALYSIS MODEL DESCRIPTION

In order to evaluate the ability of the proposed earth heat pipe system to prevent preferential icing of highway bridges, a complete thermal (nodal) mathematical model was set up to simulate the integrated earth/bridge heat pipe system. The model included a representation of the adjacent roadway and subsoil so that the ability of the design to prevent preferential icing could be evaluated.

In accordance with standard analytical procedures, the model consists of a network of lumped thermal masses, or nodes, which are connected via conductances. Figures B-1 through B-2 describe the basic model setup. Subroutines were written and included to simulate heat pipe performance, valve activation, solar heat loads, and climatic conditions (rain, snow, cloud cover, etc).

Since the event to be evaluated may typically occur over intervals as small as 5 to 15 minutes, the heat transfer at the bridge deck and adjacent roadway surfaces must be carefully treated. For conservatism, a very thin layer of the surface is assumed to be thermally connected to the atmosphere and deck and roadway slabs. A subroutine thus was written to perform an energy balance at the surface nodes for each iteration of the program, such that the surface is essentially a zero-mass node.

The following energy balance occurs at the surface nodes, figure 95:

$$q_{solar} + q_{slab - surface} = q_{convective} + q_{radiative} + q_{latent} + q_{sensible} + q_{evaporation}$$

Figure 96 summarizes the analytical expressions (except for those for incident solar energy) used to calculate each of these energy terms; the incident solar energy data were obtained from the U.S. Weather Bureau and input into the analysis in table form. A brief description of how each of these expressions was included in the analysis is presented in the following paragraphs:

B.1 SOLAR LOAD

The solar energy absorbed by the surface was determined from hourly weather data from the Weather Bureau and input into the program in table form.

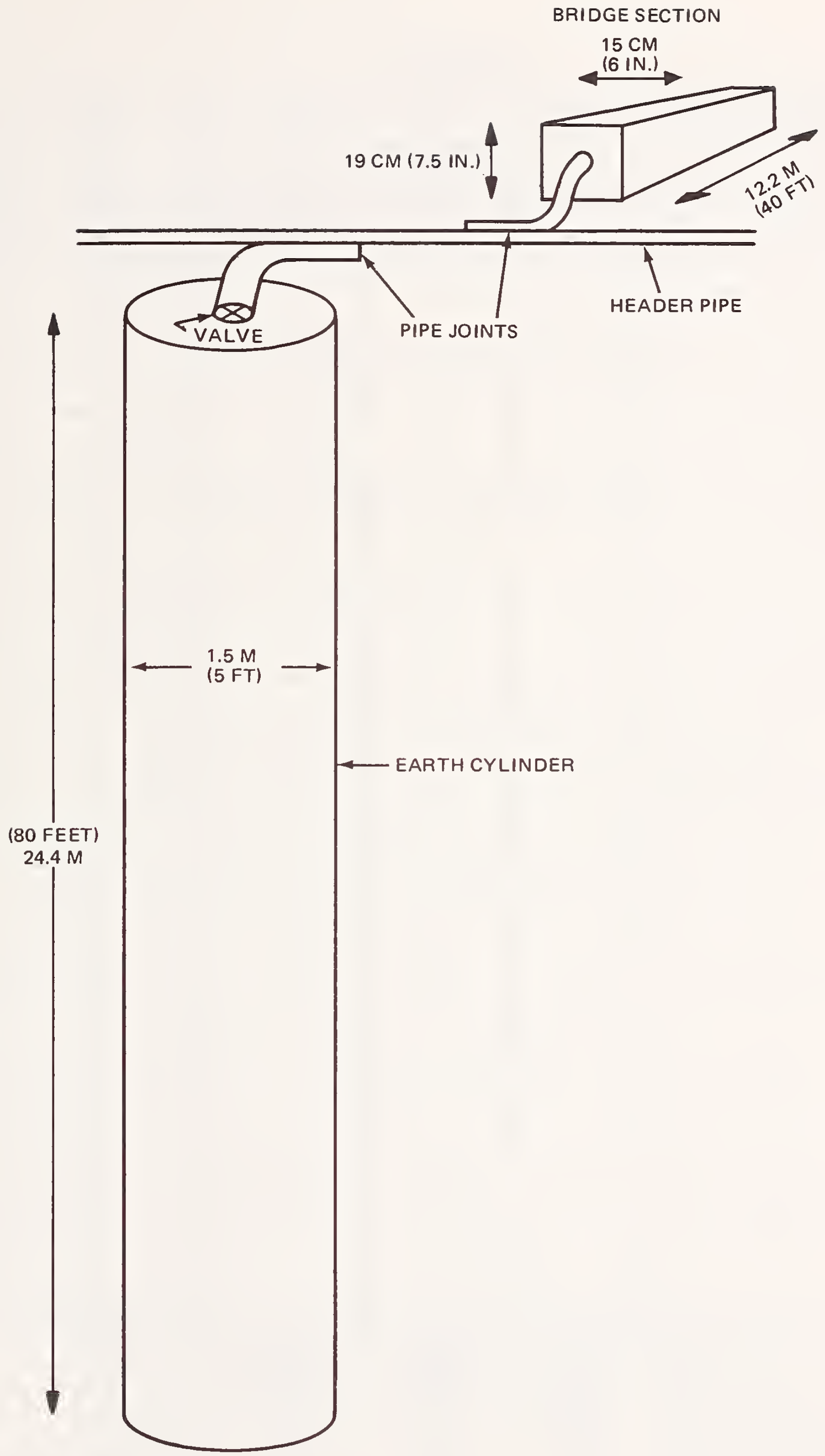


Figure B-1 Earth heat pipe de-icing system

AIR NODE 201

HEAT PIPE NODE 202

217	218	219	220	221	222	223	224	
28	40	52	64	76	88	100	134	0.6 M (2 FT)
29	41	53	65	77	89	101	135	0.6 M (2 FT)
30	42	54	66	78	90	102	136	0.6 M (2 FT)
31	43	55	67	79	91	103	137	0.6 M (2 FT)
32	44	56	68	80	92	104	138	1.2 M (4 FT)
33	45	57	69	81	93	105	139	1.2 M (4 FT)
34	46	58	70	82	94	106	140	1.2 M (4 FT)
35	47	59	71	83	95	107	141	1.5 M (5 FT)
36	48	60	72	84	96	108	142	1.5 M (5 FT)
37	49	61	73	85	97	109	143	30 M (10 FT)
38	50	62	74	86	98	110	144	6.1 M (20 FT)
39	51	63	75	87	99	111	145	6.1 M (20 FT)
1.51 CM (0.594 IN.)	2.20 CM (0.875 IN.)	3.44 CM (1.358 IN.)	5.3 CM (2.103 IN.)	8.3 CM (3.265 IN.)	12.85 CM (5.060 IN.)	20 CM (7.835 IN.)	20 CM (7.910 IN.)	

Figure B-2 Earth model

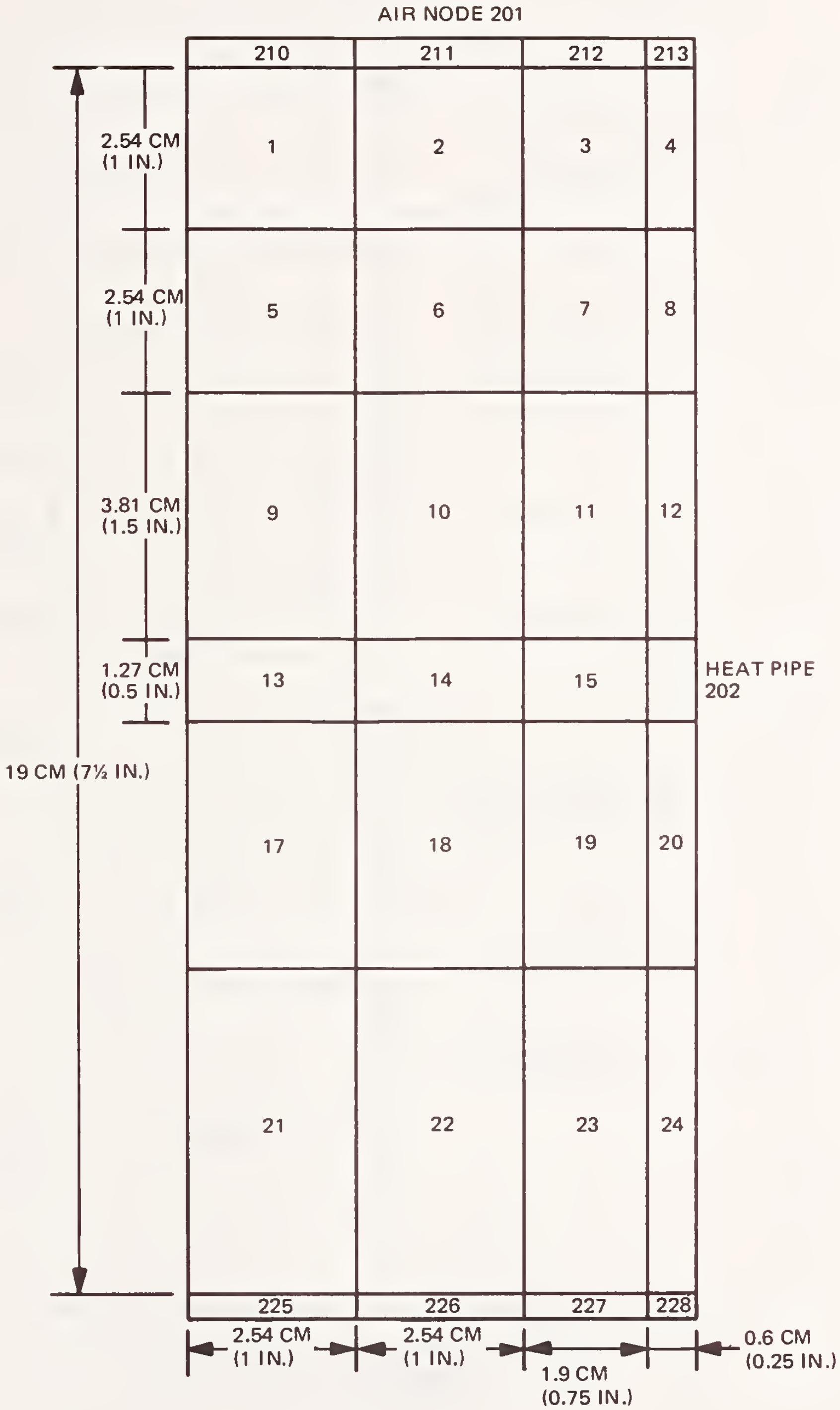


Figure B-3 Bridge model network

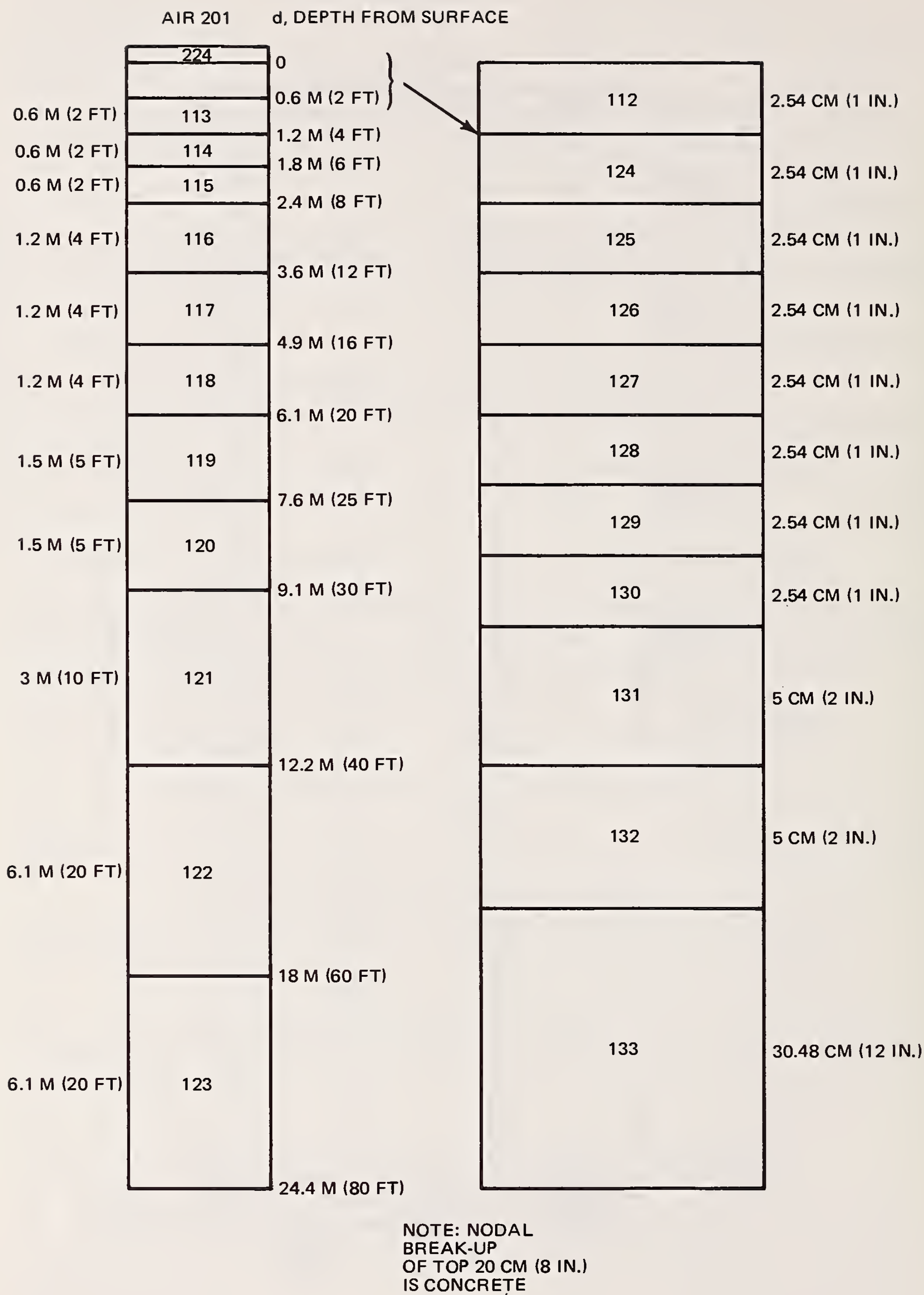
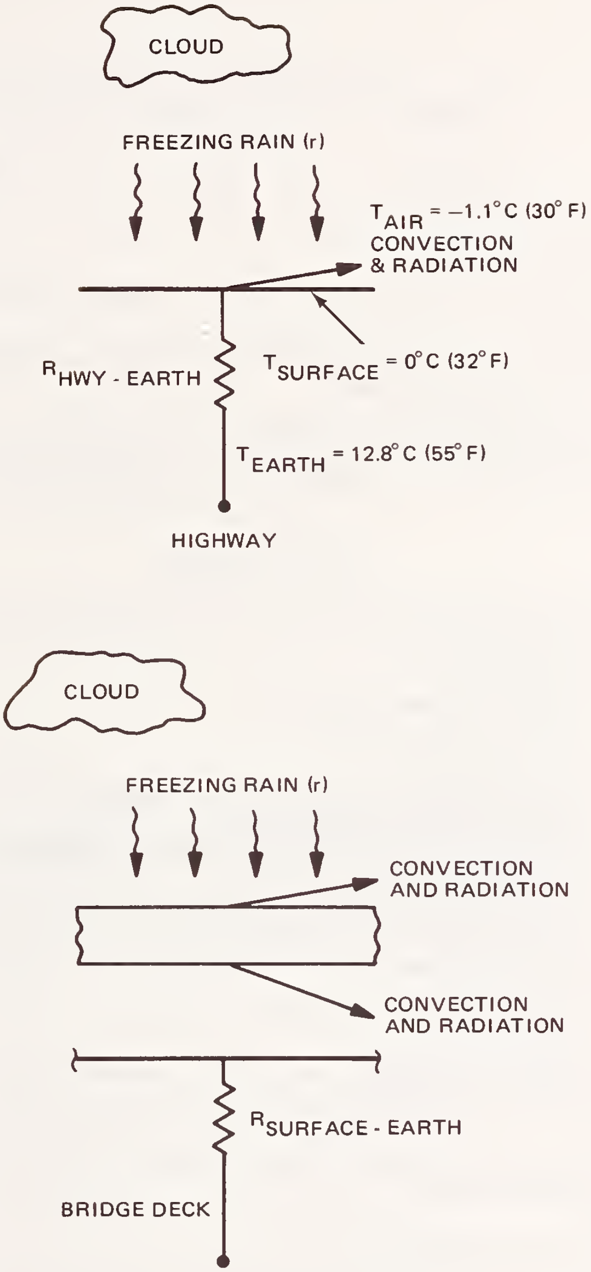


Figure B-4 Road model network



$$q_{EVAPORATION} = q_{SENSIBLE + LATENT} + q_{EVAPORATION} + q_{CONVECTION + RADIATION}$$

Figure B-5 Thermodynamics of icing

$q_{deicing} = q_{conv} + q_{rad} + q_{evap} + q_{lat} + q_{sens}$		
Term	**Description**	**Equation**
q_{conv}	Convective heat loss from surface to atmosphere, Btu/hr ft^2	$q_{conv} = (1 + 0.3V)\ (T_s - T_{air})$
q_{rad}	Radiative heat loss from surface Btu/hr-ft^2	$q_{rad} = \sigma\, \epsilon_s\, (\overline{T}_s^4 - \epsilon_{air}\, \overline{T}_{air}{}^4)\ (1 - 0.75n)$
q_{evap}	Energy loss due to evaporation of water from surface, Btu/hr-ft^2	$q_{evap} = (0.0201V + 0.055)(P_w - P_a)h_{fg}$
q_{lat}	Heat loss from melting ice, Btu/hr-ft^2	$q_{lat} = h_{fs}\rho_i\mu$
q_{sens}	Heat to warm ice to 32°F, Btu/hr-ft^2	$q_{sens} = \rho_i \mu_i c_{pi}\ (32°F - T_{air})$

Symbol Description

V = Wind Speed, mph
T = Temperature, °F
$\overline{T}$ = Absolute Temperature, °R
T_s = Surface temperature (32° F)
T_{air} = Air temperature, °F
σ = Stefan Boltzmann constant, (0.173×10^{-8} Btu/hr-ft^2 °F)
ϵ_s = Surface emittance, typically 0.8
ϵ_{air} = Atmospheric emittance from Brunt Model (Reference 8)
n = Cloud cover in tenths
P_w = Saturation vapor pressure of water at surface temperature, inches Hg
P_a = Vapor pressure of air, inches Hg
h_{fg} = Enthalpy of water
ρ_i = Density of ice
μ_i = Volume of ice
c_{pi} = Specific heat of ice
h_{fs} = Latent heat of fusion

NOTE: For roadway surface additional energy term should be included to account for heat gained from ground (q_{gnd})

$q_{gnd} = k_{soil\text{-}roadway}\ (T_s - T_{soil})$

$k_{soil\text{-}roadway}$ = Conductance from soil to roadway, Btu/hr-°F

T_{soil} = Average soil temperature

Figure B-6 De-icing heat rate calculation

B.2 CONVECTIVE LOAD

The convective heat load at the surface may be calculated as follows, Reference 8:

$$Q = Ah\,(T_{air} - T_{surface})$$

where

Q is the heat flux

A is the node surface area

h is the heat transfer coefficient defined as $h = (1 + 0.3\ V)$ Btu/hr-ft^2-°F, and V is the wind speed in mph.

U.S. Weather Bureau air temperature and wind speed data taken at three hour intervals were input into the program.

B.3 RADIATION

The net radiation load between model surfaces and the atmosphere was calculated using Brunt's expression for effective atmospheric emissivity, see Reference 9:

$$\epsilon_{air} = a + b\ \sqrt{p}$$

where a and b are experimentally determined constants and p is the partial pressure of water vapor in the air. Unfortunately, the values of a and b vary widely with location and observer; on the basis of information provided in Reference 10, average values of $a = 0.55$ and $b = 0.33$ were used. The variation of the partial pressure of water vapor in the air does not have a significant effect on ϵ_{air}. For example, for 100 percent humidity, the value of ϵ_{air} at -1.0°C (30°F) is 0.68 while the value at 11.1°C (52°F) is 0.75.

The formula for net radiation loss at the surface, with the effect of cloud cover considered, Reference 8, can be given by

$$Q = A_{surface}\ \sigma\ (T_{surface}{}^4 - \epsilon_{air}\ T_{air}{}^4)\ (1 - 0.75\ n)$$

where σ is the Stefan-Boltzmann constant in Btu/hr-ft^2- °R^4 and n is the sky cover in tenths.

B.4 WET SURFACE LOADS

The evaporation load from a wet surface is defined, Reference 7,

$$Q_{evap} = h_{fg} A\,(0.0201V + 0.055)\,(P_w - P_a)$$

Where V is wind speed

H_{fg} is the latent heat of water, Btu/lb

P_w is the stauration pressure of water at the surface temperature, inches of mercury

P_a is the partial pressure of water at the air temperature and relative humidity, inches of mercury

P_w and P_a are inputs to the program in table form.

The latent load is treated as a surface loss due to the melting of falling ice or snow; its energy requirement may be written:

$$Q_{latent} = h_{fs}\ \dot{m}\ A$$

where h_{fs} is the heat of fusion, Btu/lb

$\dot{m}$ is the rate of ice or snow fall, inches/hr

APPENDIX C

RATIO OF TOTAL RADIATION ON A TILTED SURFACE TO THAT ON A HORIZONTAL SURFACE

From Reference 6 and figure C-1.

$$R_b = \cos \theta_T / \cos \theta_z$$

where:

R_b = Ratio of total radiation on a tilted surface to that on a horizontal surface

H_n = Incident solar radiation

H = Solar radiation normal to horizontal surface

H_T = Solar radiation normal to tilted surface

θ_z = Angle between incident solar radiation and surface normal for horizontal surface

θ_T = Angle between incident solar radiation and surface normal for tilted surface

s = Tilt angle.

Figure 3.6.2 of Reference 7 presents the hourly variation of cos θ_T and cos θ_z as a function of declination (time of year), tilt angle, and latitude. These data were used to prepare figure 98, which shows the variation of cos θ_T, cos θ_z, and R_b for a surface tilted 40 degrees toward the equator, at a latitude of 40 degrees, in January.

Integrating the R_b curve yields a value of 2.6 as the ratio of daily solar radiation incident on a surface tilted 40 degrees toward the equator to a horizontal surface, for a 40 degree latitude in January.

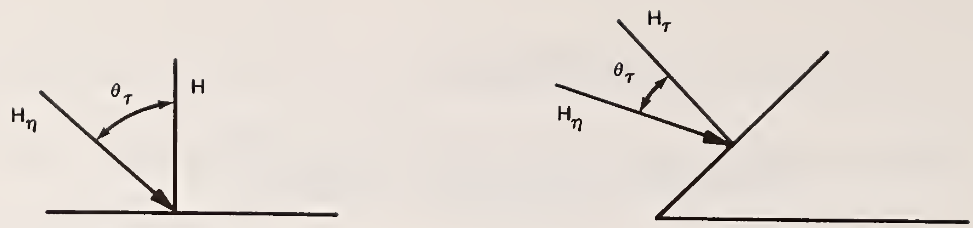


Figure 97 Radiation on a tilted surface

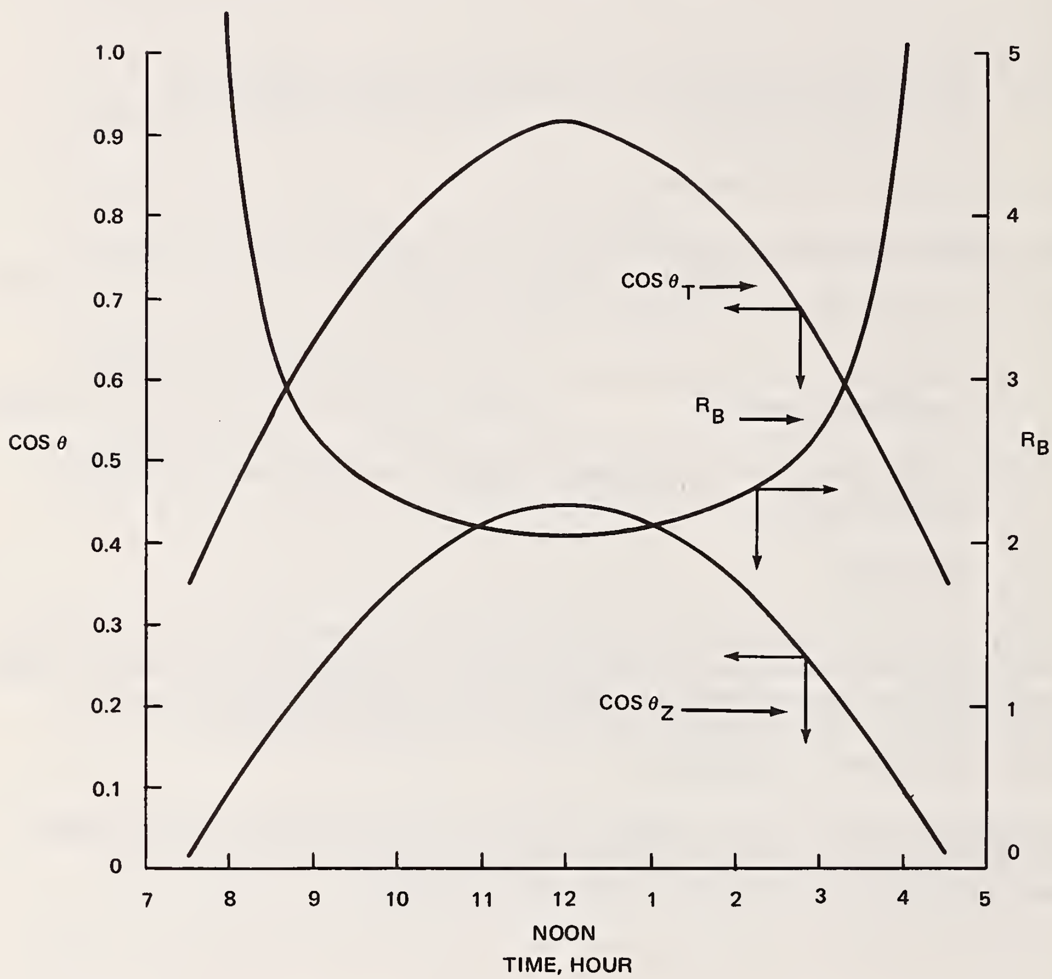


Figure C-1 Hourly variation of cos θ_T, cos θ_Z, and R_B in January for surface tilted 40 degrees to equator at 40 degree latitude

APPENDIX D

AVERAGE EFFICIENCY OF SOLAR COLLECTOR

With tank temperature assumed less than or equal to 26.7°C (80°F), the plate temperature, T_p, must be less than or equal to 32.2°C (90°F). Hence for January,

$$T_p - T_a = 32.2 - 1.1 = 31.1°C \ (90 - 34 = 56°F)$$

where T_a is the average January air temperature for New York City.

From Reference 4, the average incident solar radiation, Q_i, should be about 0.78 kwh/m^2 (250 Btu/hr-ft^2).

$$\text{Thus, } (T_p - T_a)/Q_i = 31°C/(0.78 \text{ kwh/m}^2) = 39.7°C\text{-m}^2\text{/kwh}$$
$$= 56°F/(250 \text{ Btu/hr-ft}^2) = 0.224°F - \text{hr-ft}^2\text{/Btu}$$

From this value and figure 82, the average efficiency of the solar collector, η_{sc}, is 53 percent; for design conservatism, assume η_{sc} = 50 percent.

APPENDIX E

SAMPLE CALCULATIONS OF ANALYSIS REQUIRED TO SIZE SOLAR COLLECTOR HEAT PIPE SYSTEM FOR NEW YORK CITY BRIDGE

• Mean daily solar energy incident on horizontal surface in January	= 1.5 kwh/m^2/day = 477 Btu/ft^2/day
• Ratio of energy incident on surface tilted 40 degrees to equator to horizontal surface, R_b	= 2.6
• Mean daily solar energy incident on tilted surface	= (2.6) (1.5) = 3.9 kwh/m^2/ month = (2.6) (477) = 1240 Btu/ft^2/ day
• Total monthly energy incident on tilted surface in January	= (31) (3.9) = 120.9 kwh/m^2/ month = (31) (1240) = 38,450 Btu/ ft^2/month
• Energy absorbed by collector with η_{sc} = 50%	= 0.5 (120.9) $\doteq$ 60.4 kwh/m^2/ month = 0.5 (38,450) = 19,225 Btu/ ft^2/month
• No. of icing days in January	= 9.9 days
• Monthly energy required to avoid preferential icing (since each icing event requires 120 Btu/ ft^2/day)	= 0.38 (9.9) = 3.76 kwh/m^2/ month = (120) (9.9) = 1188 Btu/ft^2/ month
• Q_{stored} (assuming that the tank must be sized to store the energy required to provide for three icing events)	= (3) (0.38) = 1.14 kwh/m^2/ = 3 (120) = 360 Btu/ft^2/bridge
• Required tank capacity, M_{tank}, for 5.55°C drop while providing 1.14 kwh/m^2	= (1.14)(103)/(5.55) (1.16) = 177 kg/m^2 or 179.41 litres/ m^2 = (360) (10) = 361b/ft^2 or 4.4 gallons/ft^2

• Tank capacity, M_{tank}, for a 465 m^2 (5000 ft^2) bridge	= (465) (179.41) = 83,425.65 litres = 5000 (4.4) = 22,000 gallons
• Insulation leak from tank (see figure 83)	= 268 kwh/month = 915,450 Btu/month
• Total energy required from solar collector	= (465) (3.76) + 268 = 2016 kwh month = (5000) (1188) + 915,400 = 6,855,400 Btu/month
• Required solar collector area, A_{sc}	= 2016/60.4 = 33 m^2 = 6,855,400/19,225 = 357 ft^2

APPENDIX F

REFERENCES

1. Blackburn, Robert R., "Economic Evaluation of the Effects of Ice and Frost on Bridge Decks," National Cooperative Highway Research Program, Midwest Research Institute Project No. 3464-E, September 1971.

2. Bienert, W. B., "Snow and Ice Removal From Pavements Using Stored Energy," Federal Highway Administration, Report No. FHWA-RD-75-6.

3. Ferrara, Angelo A. and Haslett, Robert, "Prevention of Preferential Bridge Icing using Heat Pipes" Interim Report FHWA-RD-75-111, Federal Highway Administration, July 1975.

4. Climatic Atlas of the U. S., U. S. Department of Commerce; Washington, D. C., 1968.

5. Stewart, C. F., etal, "Bridge Deck Frosting - Valley Environment, "State of California, Division of Highways, Bridge Department Research and Development Report No. 871, November 1971.

6. "Thermal Investigation and Analytical Modeling of Heat Pipe Thermal Interface Techniques," SD73-SA-0086, June 29, 1973.

7. Duffie, J. and Beckman, W., Solar Energy Thermal Process, John Wiley and Sons, New York, New York, 1974.

8. Chapman, W. P., "Design Considerations for Snow Melting," Heating, Piping, and Ventilation, November 1952.

9. Goody, R. M., Atmospheric Radiation, Oxford Press, 1964.

10. Parmelee, G.V. and Aubele, W.W., "Radiant Energy Emission of Atmosphere and Ground" Heating, Piping, and Air Conditioning, November 1951.

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